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BOSE INSTITUTE TRANSACTIONS, 1927

COLLECTED PHYSICAL PAPERS

OF

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WITH 123 ILLUSTRATIONS

LONGMANS, GREEN AND CO.
LONDON, NEW YORK, TORONTO,
BOMBAY, CALCUTTA AND MADRAS

FOREWORD

THIS book contains a collection of the papers on Physical subjects written by Sir Jagadis Bose. A considerable number of these were written some thirty years ago, shortly after the publication of Hertz's experiments on Electric Waves when the study of the properties of electric waves was being pursued with great vigour. This study was facilitated by the method introduced by Bose, of generating electrical waves of shorter wave length than those in general use. By this method he obtained important results on coherence, polarization, double refraction and rotation of the plane of polarization which are described in the papers collected in this volume. In addition to the purely physical papers there are others which describe the beginnings of Sir Jagadis' application of physical methods to the study of living matter, a subject to which most of his work in recent years has been devoted. The papers make very agreeable reading for the author is never dull. Another aspect of these papers is that they mark the dawn of the revival in India, of interest in researches in Physical Science; this which has been so marked a feature of the last thirty years is very largely due to the work and influence of Sir Jagadis Bose.

J. J. THOMSON.

IRMILY LODGE, CAMBRIDGE;
August 16, 1926.

PREFACE

A COLLECTION of papers mainly physical, dating from the year 1895, is published in the present volume. The first object of my inquiry was the optical properties of Electric Waves, brought down to within a few octaves of visible light. In the course of my investigations I was led to the discovery of electric response of non-living matter, such as metals, an account of which was published in 1900 by the International Congress of Science, Paris. The response, like that of living matter, was shown to exhibit fatigue under continuous stimulation, enhancement under chemical stimulants, and permanent abolition under poisons. These results indicated that the response of the more complex and unstable living matter is ultimately the expression of physico-chemical reactions.

My subsequent investigations were directed towards the establishment of the generalisation of the essential unity of physiological mechanism in plant and animal life. The reaction of living tissues, is greatly complicated by the combined effects induced by the fluctuating changes of the environment. This accounts for the complexity of life-movements, which are by no means capricious but are capable of rational explanation by the discovery of the combined action of different factors, the individual reactions to which are unknown to us. The external conditions can be maintained constant for only a short time during which the effect of variation of an individual factor has to be determined. This necessitates special devices for exceptionally high magnification of responsive movements, which otherwise would have been quite imperceptible. The latent period and the velocity of reaction had also to be determined with great accuracy, as also the energy of the incident stimulus.

The difficulties encountered were overcome by the successful employment of various physical methods of high sensibility and accuracy, which will be found of much service in solving not only physiological but physical problems also. A short account of some of these devices, with illustrative examples of their application, will be found towards the end of this book. The *High Magnification Crescograph* instantly records the imperceptible growth, and the variation induced in it under chemical or electrical stimulation. The *Magnetic Crescograph* records movements beyond the highest powers of the microscope, the magnification produced being about 50 million times. The *Resonant Recorder* inscribes time as short as a thousandth part of a second, and enables the most accurate determination of the *latent* or perception period of the plant and the velocity of transmission of excitation. The *Photosynthetic Recorder* automatically imprints on a moving drum, the rate of carbon-assimilation by plants. The *Magnetic Radiometer* enables relative measurement of energy of every ray of the solar spectrum. In conjunction with a special Calorimeter, a very accurate determination has been made of the efficiency of the chlorophyll-apparatus of green plants in storage of solar energy.

J. C. BOSE.

BOSE INSTITUTE, CALCUTTA;
January, 1927.

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COLLECTED PHYSICAL PAPERS

I

ON POLARISATION OF ELECTRIC RAYS BY DOUBLE-REFRACTING CRYSTALS

A beam of ordinary light incident on a crystal of Iceland spar is generally bifurcated after transmission, and the two emergent rays are found polarised in planes at right angles to each other. The object of the present enquiry is to find natural substances which would polarise the transmitted electrical ray. It was thought that the analogy between electric radiation and light would be rendered more complete if the classes of substance which polarise light were also found to polarise the electric ray. The two phenomena may be regarded identical if the same specimen is found to polarise both the luminous and the electric rays.

As the wave length of electrical radiation is very large compared with that of visible light, it may be thought that very large crystals, much larger than what occur in nature, would be required to produce polarisation of the electric ray. I have, however, succeeded in obtaining polarisation effects with crystals of moderate size. This I was able to do by reducing the length of electric waves to about 5 mm. or so.

These experiments show that certain crystals produce double refraction, and that the transmitted beams are polarised. With the help of a rudely constructed apparatus, I was able, last year, to detect traces of these effects. The apparatus has since been improved in detail; it is now possible to detect the polarisation effect with certainty.

The usual optical method of detecting the bi-refringent action of crystals, is to interpose the double refracting structure between two crossed Nicols. The interposition of the crystal generally brightens the dark field. This is known as the depolarising effect, and is regarded as a delicate test for double refracting substances. There is, however, no depolarising action when the principal plane of the crystal coincides with the polarisation planes of either the Polariser or Analyser. The field also remains dark when the optical axis of the crystal is parallel to the incident ray.

A similar method was adopted for experimenting with polarised electric radiation. A parallel electric beam is first polarised by a wire grating. A similar grating acts as an Analyser. The two gratings are crossed, and the crystal to be examined is interposed. The Receiver is a modified form of " Coherer " with its associated voltaic cell and Galvanometer. Brightening of the field is indicated by a throw of the Galvanometer needle.

Apparatus used

The following are the different parts of a complete apparatus :—

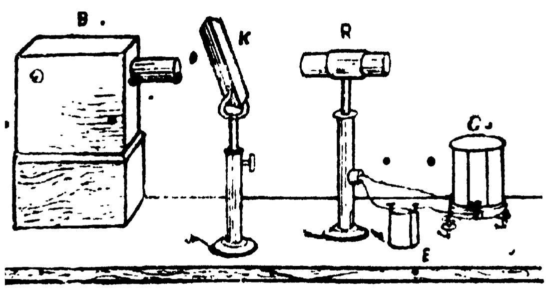

Fig. 1. Polarisation Apparatus.

B, Metallic box enclosing the Ruhmkorff coil and Radiator.
K, The crystal to be examined. E, Voltaic Cell.
C, The Galvanometer. R, tube enclosing sensitive receiver.

Radiator.—Electric oscillation is produced by sparking between hollow hemispheres, and a small interposed sphere. The two beads attached to the hemispheres and the interposed sphere were at first thickly coated with gold, and the surface highly polished. This worked satisfactorily for a time, but after long-continued action, the surface of the ball became roughened, and the discharge ceased to be oscillatory. After some difficulty in obtaining the requisite high temperature, I succeeded in casting a solid ball and two beads of platinum. There is now no difficulty in obtaining an oscillatory discharge; the sparks are made very small, as these are more effective with the receiver used. After a little experience, it is possible to tell whether the discharge is oscillatory or not. The effective sparks have a peculiar smooth sound, whereas non-oscillatory discharges give rise to peculiar cracked sound.

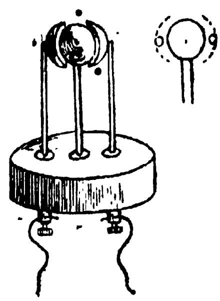
Fig. 2. The Radiator.

As an electric generator, I at first used a small Ruhmkorff coil actuated by a battery. I, however, soon found that the usual vibrating arrangement is a source of trouble; the contact points soon get worn out, and the break becomes irregular. The oscillation produced by a single break is quite sufficient for a single experiment, and it is mere waste to have a series of useless oscillations. But the most serious objection to the production of secondary sparks, unless absolutely wanted, is their deteriorating action on the spark balls.

Anyone who has tried to obtain an oscillatory discharge knows how easily the discharge becomes irregular, and the most fruitful source of trouble is often traced to the disintegration of the sparking surface. In my later apparatus, I have discarded the use of the vibrating interrupter. The coil has also been somewhat modified. A long strip of paraffined paper is taken, and tin-foil pasted on opposite sides; this long roll is wound round the secondary to act as a condenser. In this way there is a great saving of space. The two ends of the primary are in connection with a small storage cell through a tapping key. The coil, a small storage cell, and the key are enclosed in a tin-box; a small opening behind allows the stud of the press-key to pass through. In front of the box there is an opening, through which the radiating tube projects. The radiating box, thus constructed, is very portable. The one I have been using for some time past, is 7 inches in height, 6 inches in length, and 4 inches in breadth. There is another one which is still smaller.

The radiator tube is 2·5 cm. in diameter. As an instance of the efficiency of the radiating apparatus, I may here mention the fact that the storage cell was charged about a month ago; I have since been using the apparatus for electro-magnetic radiation almost every day. All the while it required no attention, and there was no further necessity of polishing the sparking surfaces. To obtain a flash of radiation I have only to press the stud and release it, and on an average, I require about fifty flashes for a day's work. For working an entire month it is therefore only necessary to have a little over a thousand breaks of the primary current. With the usual vibrating interrupter a larger number of breaks would have been necessary even for one hour's work.

Lens for rendering the beam parallel.—In my first apparatus, with the help of an ordinary glass lens and suitable diaphragms, the beam was made approximately parallel. This was more or less a guess-work, as the index of glass for the electric ray has not yet been determined. I have, however, succeeded in determining the electric index for Sulphur, which is very near 1·734. With the knowledge of this index, a cylindrical lens of Sulphur has been constructed, whose focal distance is known with accuracy. The source of radiation, the spark gap, is a line, and the lens is adjusted till its focal line and the spark gap coincide. In this way, a parallel beam of electric radiation is obtained.

Polariser and Analyser.—The success of the experiment depends greatly on the care with which the Polariser and the Analyser are constructed. Fine copper wire, 0·2 mm. in diameter, was carefully wound in parallel lines round two thin sheets of mica; there were about 25 lines in one centimetre. The mica pieces were then immersed in melted paraffin, and the wires thus fixed *in situ.* By cutting round, two circular pieces containing the gratings were obtained. One of these acted as a Polariser and the other as an Analyser.

Receiver.—The receiving circuit consists of a spiral-spring coherer in series with a modified Daniell cell and an aperiodic galvanometer of D'Arsonval type.

In a square piece of ebonite a shallow rectangular depression is cut out, and a single layer of steel spiral springs 2 mm. in diameter and 1 cm. in length is laid side by side, the sensitive surface being 1×2 cm. The springs are prevented from falling by a glass slide in front. The spirals may be compressed by means of a brass piece which slides in and out by the action of a screw. The resistance offered by this portion of the circuit can, therefore, be gradually varied. An electrical current enters along the breadth of the top spiral and leaves by the lowest spiral, having to traverse the intermediate spirals along the numerous points of contact. The resistance of the receiving circuit is thus almost entirely concentrated at the sensitive contact-surface, there being little useless short-circuiting by the mass of the conducting layer. When electric radiation is absorbed by the sensitive contacts, there is a sudden diminution of resistance, and the galvanometer is violently deflected.

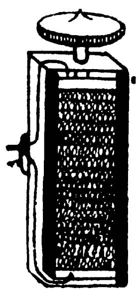

Fig. 3. The Spiral-spring Receiver.

A pair of insulated wires from the ends of the receiver are led out to a galvanometer placed at a distance. The leading wires are shielded from radiation by enclosing them inside two coatings of tin-foil. As an additional precaution, the galvanometer and the voltaic cell are also enclosed in a metallic case with a slit in front of the galvanometer mirror. A spot of light reflected from the mirror is received on a scale. By adjusting the electromotive force of the circuit, the sensitiveness of the receiver may be increased to any extent desirable.

This is most simply effected by the following arrangement of a modified Daniell cell and a shunt. A small

U tube is taken and the two limbs filled with copper sulphate and sulphuric acid, respectively; the bent portion of the tube is plugged with asbestos to prevent rapid mixing of the two liquids. A sliding ebonite piece carries a rod of zinc and a rod of copper, which are plunged in the two electrolytes. The cell is shunted with a resistance of about 10 ohms and the current flowing through the shunt, and therefore the derived E. M. F. is varied by varying the resistance of the cell by raising or lowering the electrodes. When no current is required, the rods are raised out of the liquids. A cell thus constructed is ready for use at a moment's notice, and will work for several days. The receiving circuit does not respond to the incident radiation unless a suitable E. M. F. acts on the circuit. The above simple method of adiusting the proper E. M. F. will be found very simple and effective.

When the Polariser and the Analyser are properly constructed, and the two exactly crossed, no radiation can reach the sensitive surface, and the galvanometer will remain unaffected. The field is then said to be dark. Any slight rotation of either the Polariser or the Analyser partially restores the field, and the galvanometer spot of light then sweeps across the scale.

Method of Experiment

The spark gap of the Radiator is adjusted in a vertical line. The wires of the Polariser are horizontal, and the transmitted electric ray is plane-polarised, its plane of vibration being vertical. The Analyser is now adjusted in a crossed position; on producing a flash of radiation by a single break of the primary, there is no effect on the galvanometer. The crystal to be examined is now interposed with its principal plane inclined at 45° to the horizon.

RHOMBOHEDRAL SYSTEM

(1) *Beryl*.—The first piece experimented on was a large crystal of Beryl. It is a hexagonal prism with basal planes. The specimen examined has each face 11×5 cm. The three axes lying in the same plane are inclined at 60° to each other, the fourth axis, which is also the optical axis, is at right angles to the plane containing the other three. The crystal was optically opaque.

On interposing this block with its principal plane inclined at 45°, the galvanometer spot flew off the scale. The crystal had thus produced the well-known depolarising action. The crystal was now turned round till its principal plane coincided with the vibration plane of the Polariser. There was now no action on the galvanometer. On continuing the rotation, the galvanometer at once responded. The spot became quiescent a second time, when the principal plane coincided with the plane of vibration of the Analyser.

The crystal was now placed with its optical axis parallel to the direction of the incident ray. There was now no action on the galvanometer. Rotation of the crystal round this axis did not produce any effect on the galvanometer. The field continued to be dark.

The piece of Beryl used in the above experiment was unusually large. But in the following experiments the crystals were quite small.

(2) *Apatite*.—In repeating the experiment with this crystal, strongly marked double refraction effect was exhibited.

(3) *Nemalite.*—This is a fibrous variety of Brucite, silky in appearance. In its chemical composition it is a hydrate of magnesia. This specimen exhibited a very strong depolarisation effect with a thickness of less than one cm.

RHOMBIC SYSTEM

Barytes.—A piece of this crystal was found to be strongly double-refracting.

TRICLINIC SYSTEM

Microcline.—This is a greenish blue crystal of the double oblique type. It exhibited polarisation effect in a remarkable degree.

REGULAR SYSTEM

Rock Salt.—A large piece of this crystal did not produce any effect. This is what was expected.

Having satisfied myself of the fact that systems of crystals, other than regular, produce double refraction and consequent polarisation of the electrical ray, I tried the action of electric radiation on crystals ordinarily used in optical apparatus.

I got a fairly large piece of black Tourmaline. On interposing this with its plane inclined at 45°, there was prompt movement of the spot of light. There was no galvanometric indication when the principal plane of the Tourmaline coincided with the vibration planes of either the Polariser or the Analyser.

With ordinary light, a piece of Tourmaline of *sufficient* thickness absorbs the ordinary, but transmits the extraordinary ray. With the piece of Tourmaline used in the last experiment, I found both the rays transmitted, but, it seemed to me, with unequal intensities. In other words, one ray suffers greater absorption than the other. It seems probable that with greater thickness of crystal one ray would be completely absorbed. I found other crystals behaving more or less in the same way. I reserve for another communication particulars of experiments bearing on this subject.

Lastly, I tried an experiment with a crystal of Iceland Spar taken out of a polarising apparatus. With this I got distinct depolarising action.

Summary.—Crystals which do not belong to the Regular System, polarise the electric ray just in the same way as they do a ray of ordinary light. Theoretically, all crystals, with the exception of those belonging to the Regular System, ought to polarise light. But this could not hitherto be verified in the case of opaque crystals. There is now no such difficulty with the electric ray, for all crystals are transparent to it. As a matter of fact, all the above experiments, with one exception, were performed with specimens opaque to light, and it was an interesting phenomenon to observe the restoration of the extinguished electric radiation, itself invisible, by the interposition of what appears to the eye to be a perfectly opaque block of crystal, between the crossed gratings.

(*Asiatic Soc. of Bengal, May* 1895.)

II

ON A NEW ELECTRO-POLARISCOPE

In a paper read before the Asiatic Society of Bengal "On Polarisation of Electric Rays" (May, 1895), I gave an account of some experiments which showed that crystals which do not belong to the Regular System, produce double-refraction of the electric ray, and that the refracted beams are plane-polarised.

Among the numerous crystals examined, I found some exhibiting the so-called depolarising action in a very marked degree, even when the thickness of the crystal was less than the wave-length of the electric radiation. I found, for example, Nemalite, a fibrous variety of Brucite, exhibiting this action with pieces which were comparatively thin. Different varieties of Satin Spar, Serpentine, Tourmaline and a few others were found to be very effective depolarisers.

From the various experiments to be presently described, I was led to suppose that these crystals transmit the ordinary and the extraordinary rays with unequal intensities. It would thus seem possible to quench one of the two rays by absorption, ordinary radiation after transmission through these crystals thus becoming plane-polarised. It should, however, be mentioned here, that crystals as a rule are far more transparent to electric radiation than to ordinary light, and as a consequence greater thickness of crystals would be required for the complete absorption of one of the two rays.

The apparatus with which the following experiments were carried out, consists of a Radiator emitting short electric waves, a cylindrical lens of sulphur for rendering the electric beam parallel, a pair of Analyser and Polariser, and a Receiver for detecting the electric radiation.

Electric oscillation is produced by sparking between two small platinum beads attached to hollow hemispheres and an interposed small platinum sphere (*cf.* fig. 1). The two electrodes are connected with the secondary ends of a modified Ruhmkorff coil. The usual vibrating interrupter was found to be a source of trouble, and was therefore rejected. A flash of radiation consisting of many electric oscillations is sufficient for a single experiment, and this was easily obtained by a sudden break of the primary current. To economise space, the coil was taken out of the supporting condenser box. Long strips of paraffined paper with tin-foil coatings were wound round the coil, and appropriate connections made with the interrupting key. The coil, about three inches in diameter and five inches in height, was placed vertically at one end of a small tinned-iron box, 6×4×7 inches. The metallic box screens the Receiver from electric and magnetic disturbances produced by the making or breaking of the primary current, the electric radiation being transmitted through a tube along the desired direction.

The box also contains a small storage cell and a tapping key, the press button projecting out of the box through a small hole. In front of the box there is a tube one inch in diameter and three inches long. To the inner end of this tube is fixed an ebonite square on which the radiator is mounted.

Polariser, Analyser and the Crystal-holder

At the further end of the tube is placed the Polariser, which may be a grating or any other form of Polariser, to be presently described. By means of a variable diaphragm at the end of the tube, the amount of electric radiation for an individual experiment may be varied.

Next to the Polariser is the crystal-holder, which allows the principal plane of the crystal to be inclined at any azimuth.

The Analyser is similar in construction to the Polariser, and is mounted at the open end of the cell containing the sensitive Receiver, which is a spiral spring coherer, with numerous points of contact.

The resistance of the coherer varies within wide limits. The one I use gives the best result when the resistance is reduced by compression to about 4,000 ohms ; the corresponding current circulating round the circuit is then about 10^{-4} ampere. The incident radiation reduces this resistance to 10 ohms or less. The sudden increase of current, due to the diminution of resistance, produces a deflection of the spot of light reflected from the galvanometer.

The coherer is enclosed in a small metallic cell open in front for the reception of the Analyser. The metallic cell has also a tubular projection behind, through which the wires from the ends of the coherer pass out.

Adjustable E. M. F. and the Galvanometer

The wires from the ends of the coherer lead to an adjustable E. M. F. and a dead-beat galvanometer of D'Arsonval type. The wires are placed within a double coating of tin-foil, and the galvanometer and the voltaic cell enclosed in a metallic case with a slit for the passage of the reflected spot of light. These precautions are taken for shielding the receiving circuit from the disturbing action of stray radiations.

The sensitiveness of the Receiver depends greatly on the proper adjustment of the E. M. F. For all-round work, an E. M. F. of about ·45 volt, is best suited with the particular coherer used in my experiments. This was obtained from an Iron-Zinc cell, the Iron being immersed in a solution of ferric chloride, and Zinc in dilute sulphuric acid. After the Receiver has been subjected to radiation for a length of time, its sensibility is diminished ; this may be restored by slightly increasing the E. M. F. The Receiver is placed in a derived circuit, the main current, and therefore the derived E. M. F., being varied by means of a rheostat.

Method of experiment

When the spark-gap is vertical, the electric radiation is to a great extent polarised, the vibration being accompanied by electric force in a vertical plane, and magnetic force in a horizontal plane. I shall, for simplicity, consider only the electric vibration. When the partially-polarised radiation is transmitted through a horizontal grating, the emergent beam is completely polarised, the vibration taking place in a vertical plane passing through the axis.

The spiral-spring coherer itself exhibits selective absorption. It absorbs more readily vibrations parallel to its length. Thus, when the spark-gap and the coherer are parallel, the response is very energetic, whereas the response is but feeble when the two are crossed. The analysing action of the coherer becomes more complete if it be further provided with an Analyser grating with wires perpendicular to the length of the coherer.

There are two principal positions of the Polariser and the Analyser :—

(1) *Parallel position.*—When both the gratings are horizontal.

(2) *Crossed position.*—When the polarising and analysing gratings are at right angles to each other.

In the first position, the radiation being transmitted through both the gratings, falls on the sensitive surface, and the galvanometer responds. The field is then said to be bright, In the second position the radiation is extinguished by the crossed gratings, the galvanometer remains unaffected, and the field is said to be dark. But on interposing certain crystals with their principal planes inclined at 45° to the horizon, the field is partially restored, and the galvanometer spot exhibits large deflection. This is the so-called depolarising action of double-refracting substances.

Experiment with Serpentine

I obtained a piece of fibrous Serpentine of greenish colour from the Geological Department of India; its thickness was about 2 cm. I interposed it with its fibres inclined at 45°, between the crossed Polariser and Analyser. There was at once a restoration of the field.

The Polariser and the Analyser were now made parallel, and the piece of Serpentine placed with its fibres vertical or parallel to the vibration of the electric ray; the galvanometer now ceased to respond, proving the complete absorption of the ray by the Serpentine.

The piece of Serpentine was now held with the fibres horizontal, and the radiation was found to be copiously transmitted.

In other words, *Serpentine transmits vibrations perpendicular to the fibres, but absorbs vibrations parallel to the fibres.* Ordinary radiation would thus, after transmission through Serpentine, be plane-polarised, the vibration taking place perpendicular to the fibres. To ensure complete polarisation, the piece should be fairly thick.

An efficient Polariser or Analyser can thus be made of substances like Serpentine, provided that the thickness is sufficiently great.

Satin Spar, Tourmaline and Nemalite

I also found different crystals exhibiting unequal transparency to polarised radiation in different directions. Satin-spar exhibits it, the electric vibration being more easily transmitted across the fibres. I next tried some experiments with a piece of black Tourmaline about 2 cm. in thickness. With this thickness, it was not possible to obtain complete extinction, unless the intensity of the incident radiation was considerably diminished. I at first arranged the Polariser and the Analyser parallel, and the Tourmaline was successively held vertical and horizontal. The Receiver responded with unequal intensities, the response being more energetic *when the length of Tourmaline was parallel to the electric vibration.* With fibrous varieties of crystals, I found the vibration, as a rule, more easily transmitted perpendicular to the length of fibres.

I now held the Tourmaline horizontal, and by varying the aperture at the end of the radiating tube, diminished the amount of radiation, so that at a certain point there was no response in the Receiver. On now holding the Tourmaline vertical, the Receiver at once responded.

I next experimented with a piece of Nemalite. The crystal I used was a very small one, only one cm. in thickness, but this comparatively thin piece exhibited unusually strong depolarising action. It is therefore highly probable that a sufficiently thick piece of Nemalite would make an efficient Polariser.

Experiment with Jute Cell

The most efficient polarising substances I have come across are the vegetable fibres. Among these may be mentioned the fibres of Aloes (Agave), Rhea (Boehmeria nivea), Pine Apple (Ananas sativus), Plantain (Musa paradisiaca).

Common jute (Corchorus capsularis) exhibits the property of polarisation in a very marked degree. I cut fibres of this material about 3 cm. in length, and built with it a cell with all the fibres parallel. I subjected this cell to a strong pressure under a press. I thus obtained a compact cell 3×3 cm. in area, and 5 cm. in thickness. This was mounted in a metallic case, with two openings 2×2 cm. on opposite sides, for the passage of the radiation.

The polarising grating was removed, and the Analyser arranged with its vibration plane vertical. The jute cell was now interposed with its fibres horizontal, and the Receiver was found to respond energetically.

The cell was now placed with the fibres vertical, and there was now not the slightest action on the Receiver.

The fibres were now inclined at 45° to the horizon. There was an immediate response in the Receiver but the radiation was completely extinguished by rotating the Analyser till the grating crossed the fibres. On continuing the rotation, the Receiver responded most when the wires of the grating and the fibres became parallel. Keeping the jute cell fixed at 45°, it was found that during one complete rotation of the Analyser, there were four positions of extinction (when the wires and fibres crossed), and four positions of maximum transmission (when the wires and the fibres were parallel).

From the above experiments, it is quite clear that a jute cell produces complete polarisation of the transmitted ray, the plane of vibration being perpendicular to the fibres.

Two jute cells were then made, and the gratings discarded. One of these acts as a very efficient Polariser, the other as an Analyser. When the two are crossed, the electric radiation is completely extinguished.

In the polarisation apparatus described above, three different types of Polariser (or Analyser) can be used :—

(1) The wire grating Polariser.

(2) Polariser made of crystals like Tourmaline or Nemalite.

(3) Jute or vegetable-fibre Polariser.

The apparatus may also be used as a Polarimeter, the rotation of the Analyser being easily measured by means of the graduated disc.

(*The Electrician, Dec.* 1895.)

III

ON DOUBLE REFRACTION OF THE ELECTRIC RAY BY A STRAINED DIELECTRIC

The following investigations were undertaken to find whether a solid dielectric becomes double-refracting to the electric ray when it is subjected to a molecular stress by unequal expansion in two directions, or by mechanical compression.

The Electric Polarisation Apparatus, previously described, was used for these experiments. The Analyser and the Polariser were crossed. The strained substance was then introduced between the crossed Analyser and Polariser.

Effect due to unequal expansion

I cast a rectangular piece of paraffin, and chilled its surface unequally by a freezing mixture. On suitably interposing this between the Polariser and the Analyser, the galvanometer spot was at once deflected, proving the double-refracting nature of the strained dielectric. The piece was cast six months ago. It retains its unannealed property even now.

I took two zinc tubes, one cylindrical and the other rectangular, and made castings of melted pitch, which set on cooling. In the cylindrical tube the strain was the same in all directions at right angles to the axis, and this cylindrical mass of pitch did not exhibit any double-refraction. But in the tube with the square section, unequal strain was evident in rectangular directions, perpendicular to the axis; two of the opposite sides bulged out, and the other two bulged in. On interposing this piece between the crossed Polariser and Analyser, it exhibited double-refraction.

Effect due to compression

It appeared that stratified rocks, which, from the nature of their formation, were subjected to great pressure, would serve well for the purpose of this experiment. My anticipations were verified, as the following experiments will show :—

I took a cube of Sandstone, about 5 cm. on each side, and held it between the Polariser and the Analyser, *with the plane of stratification* inclined at 45°. The galvanometer at once responded.

I then rotated the piece of rock, and adjusted it with its *plane of stratification parallel to the vibration plane of the Polariser. There was now no depolarisation effect*, the galvanometer remained unaffected. On further rotation in the same direction, the depolarisation effect re-appeared, to disappear again when the plane of stratification was made parallel to the vibration plane of the Analyser.

Experiments with many other rocks, gave similar result.

(*The Electrician, Dec.* 1895.)

IV

ON THE DETERMINATION OF THE INDEX OF REFRACTION OF SULPHUR FOR THE ELECTRIC RAY

The indices of refraction of transparent substances have been determined by the usual optical methods. There are, however, numerous substances like the various rocks, wood, brick, coal-tar, and others which are not transparent to light, so that their indices could not be determined. These substances are, nevertheless, transparent to electric radiation; the present investigation was therefore undertaken to find a direct method of determining their indices with a high degree of accuracy.

Even in the case of optically transparent substances, the indices are only known for the narrow range of light waves. For greater wave lengths, the index is inferred from Cauchy's formula. Professor Langley has, however, shown that this formula fails to give trustworthy results when applied to the dark radiations in the infra-red region of the spectrum. It does not, therefore, seem at all likely that it will give any reliable results when applied to the electric radiation.

For the determination of the index for the electric ray, the prism method is unsuitable. In the well-known Hertzs' experiment with the pitch prism, the deviation of the refracted rays extended from 11° to 34°. The approximate value of $\mu = 1{\cdot}69$, obtained from this experiment, is probably higher than the true value by about 15 to 20 per cent.

For the accurate measurement of deviation, the effect produced by radiation on the receiver should undergo an abrupt variation. When the radiation passes from an optically denser to a lighter medium, then at a certain critical angle of incidence, the radiation is totally reflected. From the critical angle the index of refraction is easily determined. The great advantage of this method lies in the fact that the transition from refraction to total reflection is very sudden.

I have determined the μ of various substances for the electric ray, by the method of total reflection, which gives very accurate results.

The refracting substance cut out or cast in the form of a semi-cylinder, is mounted on the central table of a spectrometer; the electric ray is directed towards the centre of the spectrometer, and its direction is always kept fixed. It strikes the curved surface and is refracted into the denser medium without any deviation. It is then incident on the plane surface of the semi-cylinder and is refracted into the air beyond.

The incident angle on the plane surface is increased or decreased by rotating the central table on which the cylinder rests. In practice, it is more convenient to

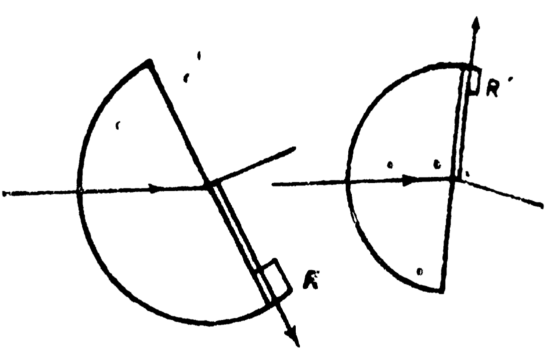

Fig. 4. The refracting semi-cylinder and the Radiator at R and R'.

commence the experiment with an angle of incidence greater than the critical angle, the incident ray being then totally reflected. The angle of incidence is next slowly decreased till its value is slightly less than the critical. At this point the ray is refracted into the air, making an angle of 90° with the normal to the surface; a receiver fixed against the side of the semi-cylinder at R, responds to the refracted radiation. A slight increase of the angle of incidence produces total reflection and the receiver ceases to respond.

The platform on which the cylinder rests, carries the usual index. Rotation of the cylinder in a left-handed direction gives a reading for total reflection. A second reading is obtained by rotation of the cylinder in the opposite direction, the receiver being now at R′. The difference between the first and the second reading is evidently equal to twice the critical angle.

A metallic screen with a small central opening is placed against the plane face of the semi-cylinder for utilising only the central rays. In order that all the rays should undergo total reflection simultaneously, it is necessary that the rays incident on the plane of separation of the two media should be parallel. This is effected by the cylinder itself. From the approximate value of μ found from a preliminary experiment, the focal distance of the semi-cylinder is roughly calculated. The spark-gap of the radiator is placed at this focus, and the rays thus rendered nearly parallel. Each subsequent experiment gives a more accurate value of μ, and from the corrected value of the focal distance thus obtained, a more accurate adjustment is made for the next experiment.

Apparatus Used

The apparatus used consists of an electric radiator emitting short waves, a large graduated circle provided with a central circular platform on which the refracting substance is placed, and a receiver, which responds to the electric radiation.

The Radiator.—Electric oscillation is produced by sparking between two metallic beads and an interposed metallic sphere one cm. in diameter. By a single sudden break of the primary in a Ruhmkorff's coil, a flash of radiation is emitted. The spark gap is placed at one end of a brass tube 5 cm. in diameter. By a sliding arrangement, the length of the tube can be varied. The Ruhmkorff's coil is enclosed in a copper box.

The Circle.—The circle has a diameter of 45 cm., and is graduated into degrees, but one-fourth of a degree can be easily estimated. The circle, as a whole, may rotate round a vertical axis which passes through the centre of a massive stand. There is a raised circular platform at the centre of the circle on which the refracting substance is placed. This platform carrying an index, can be rotated independently of the large circle. When the platform index is clamped, the two circles rotate together.

The Refracting Substance.—For substances which can be cast, the molten mass is poured into a cylindrical mould with a thin partition in the middle. In this way two equal semi-cylinders are obtained at each casting. Substances like wood or stone are turned, and the cylinder sawn into two equal halves; In my experiments, different sized cylinders were used; I have successfully used small ones with a radius of 8 cm. only. But when the cost of the material is not prohibitive, it is advisable to use fairly large cylinders. The cylinders used in the following experiments were 27·4 cm. in diameter, and 10 cm. or more in height. For liquids, the cylindrical glass trough used has a diameter of 25 cm.

The tube of the radiator is fixed and points to the centre of the graduated circle. The vertical central line of the cylinder passes through the centre of the circular platform.

The Receiver.—The receiver is a modified form of the coherer. In a rectangular piece of ebonite a narrow groove is cut out. In this groove bits of coiled steel springs are arranged side by side, only one layer deep. In this way a linear receiver is constructed with a sensitive surface 2 cm. in length and 4 mm. in breadth. By means of a screw, the springs may be gradually compressed, reducing the resistance. The coherer is in a circuit with an aperiodic D'Arsonval galvanometer and a copper-iron cell. The galvanometer has a resistance of 300 ohms, and the voltaic cell has an E. M. F. of about 0·45 volt. A Daniell cell is sometimes used, with a resistance box as a shunt; the E. M. F. can thus be adjusted to suit the sensitiveness of the receiver. When the spiral spring coherer is freshly made, it is over-sensitive. On the second day it settles down to a fair condition, though for about half an hour its action is rather unsteady; but afterwards the sensitiveness becomes fairly uniform. It will maintain this state under favourable conditions for nearly an hour, after which it begins to lose its sensitiveness. It must also be borne in mind that the sparking balls also are undergoing deterioration. The sensitiveness of the coherer may be partially restored by slightly raising the E. M. F. of the circuit. In this way it is sometimes possible to work continuously for about two hours; but greater weight should of course be given to the first sets of observations, which are taken at a time when the receiver is most sensitive.

It is superfluous to add that special precautions should be taken to guard against the disturbance due to stray radiations. The walls of the room, the table, even the person of the experimenter himself may act as reflectors, scattering the rays in all directions. I spent a considerable time in trying to find a substance that will act as a good absorber. Lamp black is useless, as it reflects copiously. Blotting paper soaked in water or copper sulphate solution does produce a certain amount of absorption; but even with these a certain amount of reflection is found to take place.

By proper screening, the disturbance due to stray radiations may, however, be got rid of. The radiating apparatus, with the exception of a tubular opening, is completely enclosed in a metallic box. The radiator tube extends right up to the refracting cylinder. The leading wires from the coherer are enclosed in a double coating of tin-foil.

Method of Experiment

I first tried to determine the index of refraction of sulphur. The material used was ordinary commercial sulphur. A semi-cylinder was made, and the two positions for total reflection determined by the method which had already been described. The difference of readings found for the two positions varied from 69° to 71° and the value of the critical angle would from these experiments seem to lie between 34·5° and 35°. This approximate value for the critical angle having been obtained, the experiment was modified to secure a higher degree of accuracy.

Two equal semi-cylinders P and Q were taken and placed on the rotating table face to face, with an air space between. A metallic plate with a narrow rectangular opening was also interposed between the

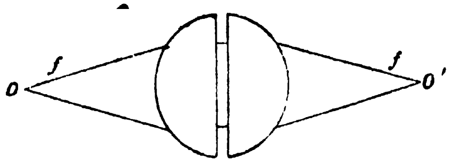

Fig. 5. Two semi-cylinders separated by air-space.

semi-cylinders to serve as a diaphragm to cut off all but the central rays. When the spark gap is placed at O, the principal focus of P, the rays emerge parallel into the air space, and are then focussed by the second cylinder at an equal distance f on the other side.

The spark gap is placed at O, and the receiver at O′, OO′ being extremities of a diameter passing through the centre of the circle. The air space is for convenience placed parallel to the index.

The platform carrying the cylinders is now rotated, say to the left. The angle of incidence is thus gradually increased, till the rays just undergo total reflection.

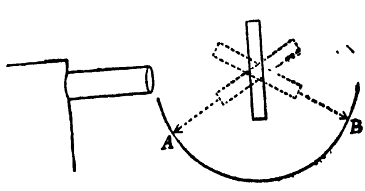

Fig. 6.
(The dotted lines represent the two positions of the air-space for total reflection.)

When this is the case the receiver ceases to respond. Let A be the corresponding reading of the platform index. A stationary index I′ is now placed opposite the reading A of the graduated circle.

When the cylinder is rotated in the opposite direction a second reading B for the critical angle is obtained. It is obvious that, neglecting errors, A—B is equal to twice the critical angle.

The platform index is now clamped and the circle as a whole is rotated till B comes opposite to the fixed index I′. The circle is now clamped, the platform arm unclamped, and the central table rotated till another reading C for the critical angle is obtained. Then, as in the previous case, B—C=$2i$, where i is the critical angle. The circle as a whole is now rotated till C comes opposite the fixed index.

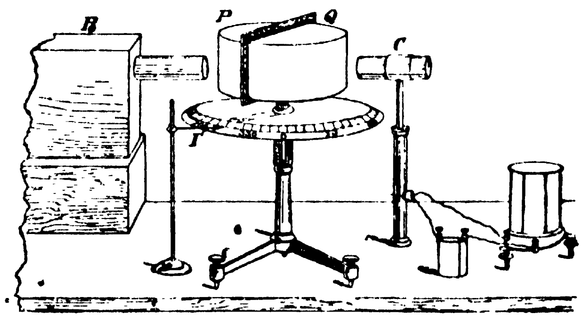

Fig. 7. R, the Radiator; C, the Receiver.

Thus at each successive operation the circle is rotated past the fixed index through $2i$. The successive difference of readings of the circle in reference to the fixed outside index, thus gives a series of values of $2i$.

The result will be more accurate if we take the mean readings $\frac{1}{2}$(A+B), $\frac{1}{2}$(B+C), ..., and take their differences (cf. second and third tables given below). Successive readings are taken till the graduated circle is rotated as near as possible through 360°.

As has been said before, there are two semi-cylinders P and Q. In the first set of experiments P is turned towards the radiator, Q acting as a focussing lens. The circle at each successive operation moves in the *right-handed* direction.

In the second set of experiments Q is turned towards the radiator, P acting as the converging lens. Successive readings are taken as before, the circle now rotating in the *left-handed* direction.

It will be observed that the final results obtained from the two sets are freed from many of the outstanding errors.

I give below the results of two sets of experiments each extending through eleven observations. The receiver was in an unusually good condition for nearly an hour, and during that time I took six observations with P to the front and six more with Q in the same position. As the receiver continued to remain in a fairly responsive condition I took five more for each set. As already said, greater weight should be given to the first two sets of six readings, as being taken under the most favourable conditions.

Successive differences of the mean readings, taken with the cylinders P and Q are given below.

P . .	71	70	70·5	70·5	70·5	70	69·5	69·5	69·5	70	=701
Q . .	70	70	71	71	71	71	71	70	70	69·5	=703·5
									Mean	.	=702·25

$$i = \frac{702{\cdot}25}{2 \times 10} = 35{\cdot}11; \quad \mu = 1{\cdot}738.$$

The following are the readings in degrees for the first six sets of observations with P (*a*, *b*) or Q (*c*. *d*).

P.

	a.	*b*.	Mean.	Difference.
1 . .	216	144	188	
				71
2 . .	144	74	109	
				70
3 . .	74	4	39	
				70·5
4 . .	(360)+4	293	328·5	
				70·5
5 . .	293	223	258	
				70·5
6 . .	223	152	187·5	
				352·5...... A.

Q.

	c.	*d*.	Mean.	Difference.
1 . .	308	360+18	343	
				70
2 . .	18	88	53	
				70
3 . .	88	158	123	
				71
4 . .	158	230	194	
				71
5 . .	230	300	265	
				70
6 . .	300	360+10	335	
				352·0...... B.

Mean of A and B=352·25.

$$i=\frac{352{\cdot}25}{2\times5}=35{\cdot}22\,;\ \mu=1{\cdot}734.$$

From the results given above it would appear that the index of refraction of sulphur is very near 1·734.

The method is also well suited for liquids; no large quantity of material is required; and the results possess a high degree of accuracy.

The determination of the indices of other solids and liquids are in progress. An account of these will be given in a future communication.

(*Proc. Roy. Soc., Oct.* 1895.)

V

INDEX OF REFRACTION OF GLASS FOR THE ELECTRIC RAY

In my previous paper, read before the Royal Society on October 20, 1895, I described a method of determining the indices of refraction of various substances for electric radiation, the principle of which depends on the determination of the critical angle at which total reflection takes place. A semi-cylinder of the given substance was taken, and the angle of incidence gradually increased till the rays were totally reflected. The experiment was repeated with two semi-cylinders, separated by a parallel air-space. The advantage of the latter arrangement was that the image cast by the two semi-cylinders remained fixed. The image underwent sudden extinction when the angle of incidence attained the critical value.

The determination of the indices of refraction for long electric waves derives additional interest from Maxwell's theoretical relation between the dielectric constant and the refractive index for infinitely long waves. The relation $K = \mu^2$ has, however, been found to be fulfilled in only a few instances. The value μ is usually deduced from Cauchy's formula, which is admittedly faulty when applied to rays below the visible spectrum. It would therefore be of interest to be able to measure *directly* the index for long electric waves, and compare it with the value of K for rapidly alternating electric fields, the periodicity of which is preferably of the same order as that of the electric waves for which the index is determined.

Among the substances in which great divergence is exhibited between the values of K and μ^2, glass may be taken as typical. In the very carefully conducted series of experiments by Hopkinson the value of K (later results) was found to be 6·61 for light flint and 9·81 for extra dense flint glass. He found no variation of K with the time of charge, which varied from 1/4 to 1/20,000 part of a second.* Messrs. Romich and Nowak † found the value to be 7·5 for alternation of field of about once in a second, while for steady fields they obtained the abnormally high value of 159. Schiller ‡ found K for plate glass to be 6·34, with a frequency of alternation of 25 in a second. With a higher frequency of about $1{\cdot}2\times 10^4$, the value obtained was lower, *i.e.*, 5·78. Gordon, with a frequency of $1{\cdot}2\times 10^4$, obtained 3·24 as K for common glass.

From the experiments of Schiller it would appear that the value of K for glass diminished with the increase of frequency of alternation of the field.

Rubens and Arons § compared the velocities of propagation of electro-magnetic action through air and glass, and obtained the ratio of the velocities or $\mu=2{\cdot}33$. The deduced value of K would therefore be 5·43. M. Blondlot ‖ found K to be 2·84 when the frequency of vibration was of the order $2{\cdot}5\times 10^7$. Professor J. J. Thomson found the specific inductive capacity of glass to be smaller under rapidly changing fields than in steady ones. He deduced the value of K by measuring the lengths of wave emitted by a parallel plate con-

* Hopkinson, 'Phil. Trans.,' 1881, Part II.
† 'Wien. Ber.,' vol. 70, 1874.
‡ 'Pogg. Ann.,' p. 152, 1874.
§ 'Wied. Ann.,' vol. 42, p. 581; vol. 44, p. 206.
‖ 'Compt. Rend.,' May 11, 1891, p. 1058.

denser with air and glass as dielectrics. The value for glass was found to be 2·7.*

On the other hand, Lecher† found that the dielectric constant rose with the frequency of vibration. Thus for plate glass—

Frequency.	K.
2	4·64
2×10^3	5·09
$3{\cdot}3\times10^6$	6·50

There is thus a serious difference between the two views of the variation of K (and therefore of μ) with the frequency of vibration. In a previous paper, I alluded to the probability of the variation of μ with the frequency of vibration. The value of μ may at first undergo a diminution with the increase of frequency, reach a minimum, and then have the value augmented when the frequency rises above the critical rate. The result obtained by Lecher is, however, too divergent from the others to be explained by such a supposition.

The direct determination of μ for glass for electric oscillations of high frequency, seemed to me of interest, as throwing some light on the controversy. After the conclusion of my determination of the index for sulphur, I therefore commenced an investigation for the determination of μ for glass. This was, however, greatly delayed by repeated failures to cast glass locally and by my long absence from India. I then obtained from England two semi-cylinders of glass, with a radius= 12·5 cm. and height=8 cm.

The method of experiment followed is the same as that described in my previous paper. The radiator

* 'Roy. Soc. Proc.,' vol. 46, p. 292.
† 'Phil. Mag.,' vol. 31, p. 205.

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is placed at the principal focus (obtained from a preliminary experiment) of one of the semi-cylinders. The cylinder mounted on the platform of a spectrometer is rotated till the rays are totally reflected. From the critical angle the value of μ is deduced.

I shall here describe some modifications introduced in the apparatus, which have been found to be great improvements. One of the principal difficulties previously met with was due to the disturbance caused by stray radiation. It is to be remembered that the receiver is extremely sensitive. Comparatively long waves are found to possess very great penetrative power; shielding the receiver then becomes very difficult. Even after the receiver, the galvanometer, and the leading wires had been screened, disturbances were met with which it was difficult to localise. Part of the disturbance may have been due to the magnetic disturbance set up by the generating coil. A double box made of soft iron and thick copper removed this difficulty. But the greatest immunity from disturbance was secured by using short waves. In this case it was not at all necessary to take very special precautions to shield either the galvanometer or the leading wires, the sensitive layer in the receiver being alone affected by the radiation. I exposed the bare leading wires to the strong action of the radiator by putting them in close proximity to the source of radiation; and yet no response was observed in the galvanometer. This freedom from disturbance is not due to the opposite action on the two wires, for a single wire may be exposed to the radiation without any action on the receiver.

With small radiators the intensity of radiation is not very great. This is a positive advantage in many experiments. It sometimes becomes necessary to have greater intensity without the attendant trouble inseparable from too long waves. I have made a new radiator, where the oscillatory discharge takes place between two small circular plates 12 mm. in diameter and an interposed ball of platinum 9·7 mm. in diameter. The sparking takes place at right angles to the circular plates. The intensity of radiation is by this expedient very greatly increased.

In my previous experiments for determination of the index of refraction, I used tubes to surround the radiator. This I was obliged to do to protect the receiver as much as possible from external disturbances. But this procedure may be open to the objection that the sides of the tube may send reflected waves. It is preferable to have a divergent beam from a single source for a well-defined image after refraction. By the successful removal of the disturbing causes it is now possible to allow the radiator to be placed in open space, a plate with a rectangular aperture allowing the radiation to fall on the refracting cylinder along a given direction. The size of the plate is 26×15 cm., and the aperture is 7×6 cm. (see fig. 8). The radiator and the receiver are placed on opposite sides of the plate. Absence of disturbance due to lateral waves was tested by closing the aperture and observing whether the waves still affected the receiver by going round the plate. The plate was found to act as an effective screen.

I have hitherto preferred the null method in my experiments, as it possesses many advantages. The sensitiveness of the receiver can be pushed to the utmost extent, and observations taken when no effect is produced on the receiver. This method of total reflection also dispenses with the difficulty of making accurate measurement of the deviation produced. After obtaining the value of the index by the method described above, I wished to see whether it was not possible to obtain fairly good results by measuring the angle of refraction corresponding to a given angle of incidence. I shall presently describe the difficulties met with in these experiments, and the manner in which they were to a great extent removed.

The preliminary experiment was carried out with a single semi-cylinder. The angle of incidence was gradually increased by rotating the cylinder, and the refracted beam was followed with the receiver. In this way it was found that the rays ceased to be refracted when the angle of incidence was about 28° 30′. The critical angle is therefore 28° 30′ and

$$\mu = 2{\cdot}08 \ldots\ldots\ldots\ldots \quad (1).$$

I next used two semi-cylinders. The plane vertical face of the first semi-cylinder was placed along a diameter of the spectrometer circle. The second semi-cylinder was separated from the first by an air-space 2 cm. in breadth. The plane surfaces of the two semi-cylinders were thus separated by a parallel air-space; the first semi-cylinder rendered the beam parallel, and the second focussed the rays on the receiver placed opposite the radiator. With the radiator used, I found a thickness of 2 cm. of air-space to be more than sufficient for total reflection of the incident ray.*

On rotating the cylinders to the right and to the left, two positions for total reflection were obtained. The

* *Vide* the following paper "On the Influence of the Thickness of Air-space on Total Reflection of Electric Radiation."

difference of circle readings for these positions, equal to twice the critical angle, was found to be 58°. The critical angle for glass is therefore 29°.

$$\mu=2{\cdot}04 \qquad (2).$$

Having thus obtained the value of the index, I tried to find whether it would be possible to obtain fairly good results by measuring the deviation of the refracted ray. In the first series of experiments, I used for this purpose a semi-cylinder, with the radiator at its principal focus (the cylindrical surface being next to the radiator), so that the emergent rays were parallel. On trying to find the angle of refraction corresponding to a given angle of incidence, I could obtain no definite reading, as the receiver continued to respond, when moved through five or six degrees on either side of the mean position where the response was strongest. It must be remembered that owing to the finite length of the waves, there is no well-defined geometrical limit to either the ray or the shadow. There is, however, a position for maximum effect, and it is possible with some difficulty so to adjust the sensitiveness of the receiver that it shall only respond to the maximum intensity.

Another troublesome source of uncertainty is due to the action of the tube which encloses the receiver. When a slanting ray strikes the inner edge of the tube, it is reflected and thrown on to the delicate receiver. Unfortunately it is difficult to find a substance which is as absorbent for electric radiation as lamp-black is for light. Lamp-black in the case of electric radiation produces copious reflection. I have tried layers of metallic filings, powdered graphite, and other substances, but they all fail to produce complete absorption.

The only thing which proved tolerably efficient for this purpose was a piece of thick blotting paper or cloth soaked in an electrolyte. A cardboard tube with an inner layer of soaked blotting paper is impervious to electric radiation, and the internal reflection, though not completely removed, is materially reduced. No reliance can, however, be placed on this expedient, when a very sensitive receiver is used.

After repeated trials with different forms of receiving tubes, I found a form, described below, to obviate many of the difficulties. Instead of a continuous receiving tube, I made two doubly inclined shields, and placed them one behind the other, on the radial arm which carries the receiver. The first shield has a tolerably large aperture, the aperture of the second being somewhat smaller. The size of the aperture is determined by the wave-length of radiation used for the experiment. It will be seen from this arrangement, that the rays which are in the direction of the radial arm, can effectively reach the receiver, the slanting rays being successively reflected by the two shields. With this expedient, a great improvement was effected in obtaining a definite reading.

When the deviated rays are convergent, the receiver is simply placed behind the shields, at the focus of the rays. But when the rays are parallel, the use of an objective (placed behind the first shield) gives very satisfactory results. As objectives I used ordinary glass lenses; knowing the index from my experiments, I was able to calculate the focal distance for the electric ray. This is of course very different from the focal distance for the luminous rays. I at first used a lens of 6 cm. electric focal distance, but this did not improve matters sufficiently. I then used one with a longer focus, namely, 13 cm., and this gave much better results.

The receiver used to be previously enclosed in a metallic case, 2 cm. in breadth, with an open front for the reception of radiation. The case was to protect the receiver from stray radiations. But by the new arrangement and improved construction, these disturbances were effectively removed. I therefore discarded the use of the metallic enclosing cell, since the rays which did not actually fall on the sensitive surface might be reflected from the back of the metallic cell and thrown on to the sensitive layer. The layer of spirals, only 1·5 mm. in breadth, is laid on a groove in ebonite (which is transparent); and the linear receiver without any metallic case was placed at the focus of the lens.

I now proceeded to measure the angle of refraction corresponding to a given angle of incidence. In the first series observed, the refraction was from glass to air; the curved surface of the semi-cylinder was turned to the radiator, which was placed at its principal focus. The receiver was mounted on the radial arm with the double shields, and the objective in the manner already described. The reading for refracted rays was taken

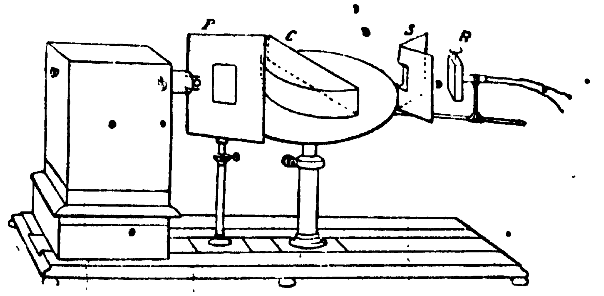


Fig. 8. The electric refractometer: P, the plate with a diaphragm; C, the semi-cylinder of glass; S, the shield (only one shown in the diagram); R, the receiver.

in the following manner. Having adjusted the semi-cylinder for a given angle of incidence, the receiver was moved round till it responded to the refracted ray. Readings were taken first by placing the receiver at an angle less than the true reading and gradually *increasing* the angle till there was a response. The receiver was then placed at a greater angle, and the angle gradually *reduced* till the receiver again responded. In this way a series of readings for a particular angle of incidence was obtained. These readings were found fairly concordant, the maximum variation from the mean being not so great as 1°. One set of readings was taken on one half of the spectrometer circle; the cylinder was next rotated in the opposite direction, and readings taken on the other side.

Angle of Incidence.	Angle of Refraction.			μ.
	Reading to the right.	Reading to the left.	Mean.	
15°	31° 0′ 31 0 31 30 31 30	31° 30′ 30 30 31 30 31 30	31° 15′	2·00
20°	45° 30′ 45 30 44 30 45 30	45° 30′ 46 0 44 0 45 30	45° 15′	2·08
22°	48° 0′ 50 0 49 30 50 0	49° 30′ 50 30 48 30 50 0	49° 30′	2·03

Mean value of $\mu=2{\cdot}04$............ (3).

In the next series of observations, the rays were refracted from air into glass. The electric beam was rendered parallel with the help of a glass lens (f=4 cm.). The beam was incident on the *plane* face of the semi-cylinder. As the cylinder itself focussed the refracted beam, the objective hitherto used in conjunction with the receiver was dispensed with.

i.	r.	Mean value of r.	μ.
40°	18° 19 18	18° 20′	2·04
50°	22° 23 22° 30′	22° 30′	2·00
65°	25° 30′ 26° 27	26° 10′	2·05

Mean value of μ=2·03........... (4).

The different values of μ obtained are given below :—

From total reflection from a single semi-cylinder . 2·08.... (1)
„ „ „ two semi-cylinders . 2·04.... (2)
From refraction from glass into air . . . 2·04.... (3)
„ „ air into glass . . . 2·03.... (4)
The frequency of vibration was of the order 10^{10}.

The value of the index of the glass for sodium light by the total reflection method was found to be

$$\mu_D = 1{\cdot}53.$$

(*Proc. Roy. Soc., Nov.* 1897.)

VI

THE INFLUENCE OF THE THICKNESS OF AIR-SPACE ON TOTAL REFLECTION OF ELECTRIC RADIATION

In my preliminary experiments on the determination of the index of refraction of various substances for electric radiation, I used a single semi-cylinder of the given substance; the electric ray was refracted from the denser medium into air, and at the critical angle of incidence it underwent total reflection. The experiment was repeated with two semi-cylinders separated by a parallel air-space. With light waves, an extremely thin air-film is effective in producing total reflection. But a question might arise whether waves a hundred thousand times as long would be totally reflected by films of air, and, if so, it would be interesting to find out the minimum thickness of air-space which would be effective in producing this result. The factors which are likely to determine the effective thickness of air-space for total reflection are: (1) the index of refraction of the refracting substance; (2) the angle of incidence; and (3) the wave-length of the incident electric radiation. In the following investigation, I have studied the influence of the angle of incidence and of the wave-length in modifying the thickness of the effective air-space. The refracting substance used was glass.

I. *Influence of the Angle of Incidence*

The experimental difficulty in these investigations lies in the fact, that there is at present no receiver for electric radiation which is very sensitive, and at the same time strictly metrical in its indications. The difficulty is further accentuated by the fact that the intensity of the electric radiation cannot be maintained absolutely constant. Attempts have been made in the following experiments to remove, to a certain extent, some of these difficulties.

Two semi-cylinders of glass, with a radius of 12·5 cm., were placed on the spectrometer circle. The plane faces were separated by a parallel air-space. The radiator was placed at the principal focus of one of the semi-cylinders ; the rays emerged into the air-space as a parallel beam, and were focussed by the second semi-cylinder on the receiver placed opposite the radiator. Electric radiation was produced by oscillatory discharge between two small circular plates having a diameter of 1·2 cm. and an interposed platinum ball 0·97 cm. in diameter.

The two semi-cylinders were separated by an air-space 2 cm. in thickness ; this thickness was found to be more than sufficient for total reflection. The critical angle for glass I found to be 29°. The experiments were commenced with an angle of incidence of 30° (slightly greater than the critical angle). The receiver, which was placed opposite the radiator, remained unaffected as long as the rays were totally reflected. But on gradually diminishing the thickness of air-space by bringing the second semi-cylinder nearer the first (always maintaining the plane surfaces of the semi-cylinders parallel), a critical thickness was reached when a small portion of the radiation began to be transmitted, the air-space just failing to produce total reflection. The *beginning* of transmission could easily be detected and the critical thickness of air determined with fair accuracy. When the thickness of air was reduced to 14 mm., the receiver began occasionally to be affected, though rather feebly. But when this was reduced to 13 mm. there was no uncertainty ; a measurable, though small, portion of the radiation was now found to be always transmitted.

I now increased the angle of incidence to 45°, and observed that the minimum thickness, which at 30° just allowed a small portion of radiation to be transmitted, was not sufficiently small to allow transmission at the increased angle of incidence. The thickness had to be reduced to something between 10·3 mm. and 9·9 mm. for the beginning of transmission.

With an angle of incidence of 60°, the minimum thickness for total reflection was found to lie between 7·6 mm. and 7·2 mm.

Angle of incidence.	Minimum thickness of air for total reflection.
30°	Between 14 and 13 mm.
45	,, 10·3 and 9·9 mm.
60	,, 7·6 and 7·2 mm.

The minimum effective thickness is thus seen to undergo a diminution with the increase of the angle of incidence.

II. *The influence of the Wave-length*

In the following experiments I kept the angle of incidence constant, and varied the wave-length. I used three different radiators, R_1, R_2, and R_3 ; of these R_1 emitted the longest, and R_3 the shortest waves.

The following method of experimenting was adopted as offering some special advantages. If a cube of glass be interposed between the radiator and the receiver placed opposite to each other, the radiation striking one face perpendicularly would be transmitted across the opposite face without deviation and cause a response in the receiver. If the cube be now cut across a diagonal, two right-angled isosceles prisms will be obtained. If these two prisms were now separated slightly, keeping the two hypotenuses parallel, the incident radiation would be divided into two portions, of which one portion is transmitted, while the other is reflected by the air film in a direction (see fig. 9) at right angles to that of the incident ray, the angle of incidence at the

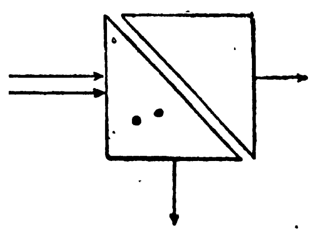


Fig. 9. Section of the two prisms.

air-space being always 45°. The transmitted and the reflected components would be complementary to each other. When the receiver is placed opposite to the radiator, in the A position, the action on the receiver will be due to the transmitted portion; but when the receiver is placed at 90°, or in the B position, the action on the receiver will be due to the reflected portion. The advantage of this method is that the two observations for transmission and reflection can be successively taken within a short time, during which the sensitiveness of the receiver is not likely to undergo any appreciable change. In practice three readings are taken in succession, the first and the third being taken, say, for transmission and the second for reflection.

I shall now give a general account of the results of the experiments. When the prisms are separated by a thickness of air-space greater than the minimum thickness for total reflection, the rays are totally reflected, there being no response of the receiver in position A, but strong action in position B. As the thickness is gradually decreased below the critical thickness, the rays begin to be transmitted. The transmitted portion goes on increasing with the diminution of the thickness of air-space, there being a corresponding diminution of the reflected component of the radiation. When the thickness of the air-space is reduced to about 0·3 mm., no reflected portion can be detected even when the receiver is made extremely sensitive. The reflected component is thus practically reduced to zero, the radiation being now entirely transmitted; the two prisms, in spite of the breach due to the air-space, are electro-optically continuous. This is the case only

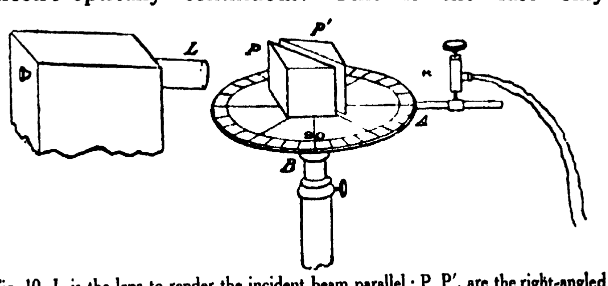


Fig. 10. L is the lens to render the incident beam parallel; P, P', are the right-angled isosceles prisms; A and B are the two positions of the receiver. The receiver-tube is not shown in the diagram.

when the two prisms are made of the same substance. If the second prism be made of sulphur, or of any other substance which has either a lower or a higher refractive index, then there is always a reflected portion even when the two prisms are in contact.

Another interesting observation was made by separating the prisms just sufficiently for total reflection. There would now be no transmitted portion. But if a thin piece of cardboard or any other refracting substance were interposed in the air-space, a portion of the radiation was found to be transmitted; it was now necessary to separate the prisms further to reduce the transmitted portion to zero. This method opens out a possibility of determining the electric index of the interposed substance.

Having given a general account of the experiments I shall now describe in detail the method of procedure. The radiator tube was provided with an ordinary lens whose focal distance for electric radiation is about 4 cm. The beam thus rendered approximately parallel fell perpendicularly on the face of the glass prism. The two prisms were made by cutting a cube of glass—an ordinary paper weight—across a diagonal. The size of the cube was 4·5 cm. on each side.* One prism was fixed on the spectrometer circle; the other could be moved so as to change the thickness of the interposed air-space between the two sections very gradually. The separation was simply effected by means of ordinary cards. The cards used were of uniform thickness, each card being 0·45 mm. in thickness. A certain number of cards were taken and placed between the prisms with their surfaces in contact with the hypotenuses. The cards were then carefully withdrawn, leaving the prisms separated by a thickness of air equal to the thickness of the given number of cards. It would, of course, be an improvement to have a micrometer screw by which the thickness can be gradually increased.

* Larger prisms would have been preferred, had they been available. The prisms after cutting were found to be approximately isosceles, the angles being 90°, 46°, and 44°.

Observations were now taken to determine the minimum thickness of air for total reflection for different wave-lengths, the angle of incidence being in all cases kept at 45°. Three radiators, R_1, R_2, R_3, were used. I have not yet made determinations of the lengths of waves emitted by these radiators, but it will be seen from the dimensions of the radiators that the waves emitted by R_1 are the longest and those emitted by R_3 the shortest. The oscillatory discharge in R_1 took place between two circular plates 1·2 cm. in diameter and an interposed ball of platinum 0·97 cm. in diameter. The radiators were enclosed in a tube 3·8 cm. in diameter.

In the radiator R_2, the discharge took place between two beads of platinum and an interposed sphere the same as in R_1. The distance between the sparking surfaces was 1·01 cm.

In the radiator R_3, sparking took place between two beads and an interposed sphere 0·61 cm. in diameter. The distance between the sparking surfaces was 0·76 cm.

One prism was fixed on the spectrometer circle, and the other was at first placed somewhat apart from it; the distance was now gradually reduced till the air-space just ceased to reflect totally, when a small portion of radiation began to be transmitted. The beginning of transmission was detected by the receiver, which was placed in the A position.

Radiator.	Distance between sparking surfaces in mm.	Minimum thickness for total reflection.
R_1	——	Between 10·3 and 9·9 mm....(*a*)
R_2	10·1	„ 7·6 and 7·2 mm. ...(*b*)
R_3	7·6	„ 5·9 and 5·4 mm. ...(*c*)

From the above results it is seen that the effective thickness of the totally reflecting air-space increases with the wave-length. If the wave-lengths are proportional to the distance between the sparking surfaces which give rise to the oscillatory discharge, the wave-lengths in (b) and (c) are in the ratio of 101 : 76. This is not very different from the ratio of the corresponding minimum thicknesses of the totally reflecting air-space.

III. *On the Relation between the Reflected and the Transmitted Components of Radiation when the Thickness of Air-space undergoes Variation*

It was stated in the general account of the experiments, that as the thickness of air-space is gradually reduced the intensity of the transmitted portion of radiation is increased, while there is a corresponding diminution of the intensity of the reflected portion. This I have been able to verify qualitatively from numerous observations. But many difficulties are encountered in making quantitative measurements, owing to the difficulty of maintaining the intensity of radiation, as well as the sensitiveness of the receiver, absolutely constant.

As regards the first, the intensity of the emitted radiation depends on the efficiency of the secondary spark, and the nature of the sparking surface. Keeping the primary current that flows through the Ruhmkorff coil constant, the efficacy of the secondary spark is very much affected by the manner in which the contact is broken in the primary circuit. If a vibrating interrupter is used, the break is apt to become irregular; the torrent of the secondary sparks also spoils the sparking surface of the radiator. For merely qualitative experiments the use of a vibrating interrupter is not so very prejudicial, as along with the ineffective discharges there are present some which are oscillatory. But where successive discharges are to give rise to radiation of equal intensity, it becomes necessary to avoid all sources of uncertainty. For these reasons I prefer a single break for the production of a flash of radiation. With some practice it is possible to produce a number of breaks, each of which is effective. If the surface at the break is kept clean, and the break is properly effected, successive flashes of radiation up to a certain number are about equally intense. When the sparking has been taking place for too long a time, the surface no doubt undergoes a deterioration. But twenty or thirty successive sparks are equally efficacious when sparking takes place between platinum surfaces. The use of a single flash of radiation is preferable on another account. The receiver at each adjustment responds to the very first flash, but becomes less sensitive to the subsequent flashes. The conditions of the different experiments are similar, when the action on the receiver is due to a single flash of radiation, instead of the accumulated effect of an unknown number of flashes.

I give below the deflections of the galvanometer produced by four successive flashes of radiation.

(1)	115 divisions.
(2)	122 „
(3)	113 „
(4)	108 „

When very careful adjustments are made, the successive deflections are approximately equal. There are, however, occasional failures, owing either to the fault of the break, or loss of sensitiveness of the receiver.

More serious is the difficulty in connection with the receiver. With the improvements adopted there is no difficulty, under any circumstances, to make the receiver very highly sensitive; but it is not easy to maintain the sensitiveness absolutely uniform. I have in my previous papers explained how the sensitiveness of the receiver depended on the pressure to which the spirals were subjected, and on the E. M. F. acting on the circuit; and how the loss of sensitiveness due to fatigue was counteracted by slightly increasing the E. M. F. For each receiver there is a certain pressure, and a corresponding E. M. F., at which for a given radiation the receiver is fully sensitive. Having obtained these conditions, the sensitiveness can be increased or decreased by a slight variation of either the pressure or the E. M. F. An increase of pressure produced by the advance of the micrometer press screw through a fraction of a millimetre would sometimes double the sensitiveness; similarly an increase of E. M. F. of even $\frac{1}{100}$ volt increases the sensitiveness to a considerable extent.

The nature of the difficulties in maintaining the sensitiveness of the receiver uniform will be understood from what has been said above. But by very careful and tedious adjustments I was however able to obtain fairly satisfactory results, and was in hopes of ultimately obtaining symmetrical values from the galvanometer deflections. The setting-in of the rainy weather has unfortunately introduced other conditions unfavourable to the maintenance of uniformity of the sensitiveness of the receiver. Owing to the excessive damp and heat the spirals get rusty in a short time, and variation in the sensibility is produced by the altered condition of the surface of the sensitive layer. The results of certain experiments I have carried out lead me to hope that this difficulty will, to a certain extent, be removed by covering the sensitive surface with a less oxidisable coating.

The deflections produced in the galvanometer can only be taken as approximately proportional to the intensity of the absorbed radiation. It would be better to observe the diminution of the resistance produced by the incident radiation. This may be done with the help of a differential galvanometer and a balancing resistance.

G is a high resistance differential galvanometer, with two sets of electrodes, A, B; C, D; one pair of electrodes is in series with the receiver, and the other with a resistance box. When the receiver is adjusted to respond to the electric radiation, a weak current flows through it. The same E. M. F. acts on both the circuits. The compensating current, produced by a proper adjustment of the resistance of the box, brings the spot of light back to zero. The resistance of the box is equal or proportional to the resistance of the receiver.

When radiation is absorbed by the receiver the resistance is decreased, and this diminution of the resistance is found from the new balancing resistance.

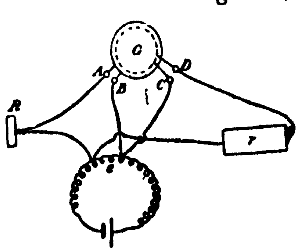


Fig. 11. G, the differential galvanometer; R, the receiver; r, the resistance box.

All observations agreed in showing that as the thickness of air-space was gradually decreased, the transmitted component was increased, with a corresponding decrease of the reflected portion. I give below two sets of observations, in which the receiver acted better than usual.

Radiator R_2; distance between the sparking surfaces=10·1 mm.

Thickness of air-space in terms of number of cards.	Thickness in mm.	Galvanometer deflection due to the reflected portion.	Galvanometer deflection due to the transmitted portion.
1	0·45	0 or very slight.	Against the stop.
2	0·90	Slight	,, ,,
4	1·8	80	160
8	3·6	145	150
10	4·5	150	120
12	5·4	160	100
16	7·2	Against the stop	30
18	8·1	,, ,,	0

It is seen from the above, that as the thickness of the air-space was gradually increased, the reflected component increased, while the transmitted portion decreased. The minimum thickness for total reflection was found to be about 8 mm. When the thickness of air-space was reduced to about half this thickness (slightly less than half) the reflected and the transmitted portions seemed to be about equal.

With the radiator R_1 the minimum thickness for total reflection was found to be equal to the thickness of 22 cards (9·9 mm.). When the thickness of air-space was reduced to the thickness of 10 cards (4·5 mm.) the reflected and the transmitted portions seemed to be about equal. As two experiments immediately following each other are more likely to be comparable, the experiments were so arranged that the observation of deflection for *transmission* with a certain thickness of air followed the observation for *reflection* with a different thickness, the corresponding deflections being about equal. As stated above, the reflected and the transmitted portions were approximately equal when the thickness of air was equal to the thickness of 10 cards. Keeping 10 as the mean, pairs of readings were taken with different thicknesses. For example, the reflection reading with a thickness of air equal to the thickness of 4 cards was followed by taking a reading for transmission, with a thickness of air equal to the thickness of 16 cards; the deflections produced in the two cases were about equal, namely sixty-six divisions of the scale.

I append below a table showing the corresponding thicknesses of air (in terms of number of cards) which gave approximately equal deflections, the deflection in one case being due to the reflected component, and in the other case to the transmitted component. The receiver was made moderately sensitive, so that the deflections lay within the scale.

Thickness of air for reflection.	Thickness of air for transmission.	Deflection produced.
4	16	66
6	14	70
8	12	90
10	10	120

When the thickness of air was reduced to 0·45 mm., a deflection of two divisions was obtained for the reflection reading. From this an approximate idea of the intensity of the reflected component may be obtained. From the table given above, it is seen that half the total radiation gave a deflection of 120 divisions. The intensity of the reflected component, with a thickness of 0·45 mm., is therefore 1/120th part of the total amount of incident radiation, on the assumption, which is only approximate, that the galvanometer deflections were symmetrical. When the thickness was reduced to 0·3 mm., no reflected component could be detected, though the receiver was made extremely sensitive.

(*Proc. Roy. Soc.*, *Nov.* 1897.)

VII

A SIMPLE AND ACCURATE METHOD OF DETERMINATION OF INDEX OF REFRACTION FOR LIGHT

The apparatus usually employed for the determination of the index of refraction is very elaborate and costly. Numerous adjustments have to be made, and a long time spent to secure accurate results. The following method for the determination of the optical index is a modification of the one which has for some time been employed by me in the determination of the index of electric refraction. The apparatus required is very simple, and I made a rough model of it at a trifling cost, and gave it to my pupils for trial. I was surprised to find how, even in their inexperienced hands, it gave results which would compare favourably with the various determinations of the indices hitherto made. The other advantages of this method are the quickness with which a determination can be made, and its adaptability to lecture demonstrations.

The method depends on the determination of the critical angle at which total reflection takes place. The principle of total reflection has also been employed by M. M. Terquem and Trannin, but the method described below is somewhat different, being much simpler, as no Collimator and observing Telescope are required. It has the additional advantage of being applicable to solids; and by a process of repetition, the value of the critical angle is obtained with a remarkably high degree of accuracy.

A beam of light is refracted from the given substance into air, and the angle of incidence gradually increased till total reflection just takes place. From the critical angle i thus determined, the index is found from the formula $\mu = \frac{1}{\text{Sin } i}$.

The necessary appliances for the determination are: (1) a hollow glass cylinder, which may be a beaker, for liquids (or a stoppered phial for volatile substances), or two semi-cylinders of the given solid; (2) a circular wooden table graduated into degrees and capable of rotation round a vertical axis. The table has at the centre a raised circular platform carrying an index. The platform can revolve round the common vertical axis independently of the table. When the platform is clamped down, the circle and the platform revolve together round a common axis.

The apparatus may be used for the following investigations :—

(1) Determination of the indices of solids and liquids.
(2) Variation of the index with the strength of different solutions.
(3) Variation of the index with temperature.
(4) Determination of the indices for the different rays, and of the dispersive power.

1. Determination of the index for liquids

A vertical rectangular plate is suspended so as to divide the liquid in the glass cylinder into two halves. A narrow central and vertical slit is cut in the rectangular plate. Two thin microscope cover slips about one cm. square are superposed and cemented with an interposed air-film, and the piece is fixed against, say, the lower portion of the vertical slit. The liquid is, of course, continuous through the upper and uncovered portion of the slit; but, in the lower portion, the air-film separates the two semi-cylinders of liquid. Light passing through one of these semi-cylinders is thus incident on the second medium, the film of air, and when the angle of incidence is sufficiently large, the beam undergoes total reflection. In order that all the rays might undergo total reflection simultaneously, it is necessary that the incident beam should be parallel.

Adjustment for rendering the beam parallel.—The diagram represents a section of the liquid semi-cylinders: the one to the left we shall call P, that to the right Q.

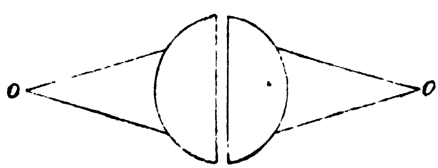


Fig. 12. The source of light O and its image at O[1].

Suppose O to be the principal focus of P; light diverging from a source O, would emerge into the air-film as a parallel beam, and would be focussed by Q at an equal distance, O′ to the right of the air-film. This will be all the more exact if a narrow diaphragm cut off all but the central rays. To render the beam incident on the air-film parallel, it is therefore only necessary to bring gradually the source of light near the cylinder, till an image is formed at an equal distance on the other side, the distances being measured from the axis of the cylinder. It will be observed that the semi-cylinder

P acts as a collimating lens, and Q as the object-glass of an observing telescope. It will also be seen that the value of the index may now be obtained with fair accuracy from the distance OO′ (which is equal to four times the focal distance of the cylinder) and the radius of the cylinder.

As the lens is cylindrical, the source of light may be a line instead of a point. A narrow slit may be illuminated by sodium light for monochromatic measurements; or the slit may be illuminated by sun-light. It is sometimes more convenient to use the incandescent filament of a glow lamp as the source of light.

Method of experiment.—The cylinder containing the liquid with the interposed air-film is placed on the platform, the axis of the cylinder passing through the axis of the graduated circle. If the cylinder is kept fixed, and the direction of incident light changed, it will be observed that there are four positions, A, B, C, D, for total reflection, the angles AOB or DOC being each equal to twice the critical angle.

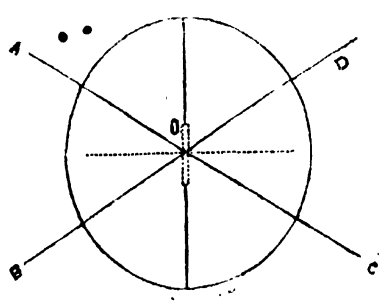


Fig. 13. Four positions for Total Reflection.

The source of light may be kept fixed, and the angle of incidence varied by rotating the central platform on which the cylinder with the interposed film is placed, till total reflection just takes place. The image produced remains fixed, till at the critical angle it suddenly disappears from the screen; this is a great advantage, as the trouble entailed in following the deflected image in the prism-method is avoided. As the cylinder revolves round, total reflection will take place four times, twice

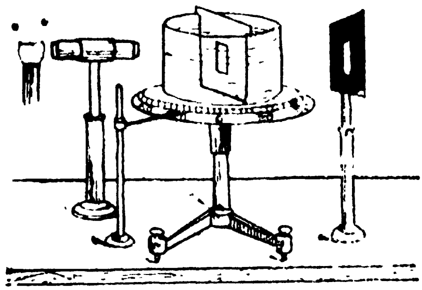


Fig. 14. The Spectrometer circle. There is a sliding tube with a slit at one end. The distance of the slit from the centre of the cylinder is adjusted till a sharp image is formed at an equal distance on the screen to the right. A vertical plate with a slit and air-film is suspended dividing the cylinder in two halves.

from the air-film surface of each semi-cylinder. The source of light and a screen being now fixed at the extremities of a diameter passing through the centre of the circle, the distance of the slit is adjusted for rendering the beam incident on the air-film parallel, in the manner already described. When the angle of incidence reaches the critical value, the image on the screen is suddenly extinguished. In the centre of the screen there is a circular aperture, behind which the eye itself may be placed to receive the light directly. When white light is used, as in the determination of the indices for the different rays, the image is cast on the slit of a small direct vision spectroscope, and the spectrum observed.

A portion of light may be allowed to pass through the upper part of the slit, where the liquid is continuous, and the corresponding portion of the image will never be extinguished. This portion of the image is used in lecture demonstrations as a marked line of reference. But in the lower portion of the image, light has to pass through the air-film, and the bright image suddenly disappears from the screen as soon as the angle of incidence exceeds the critical value.

During a complete rotation of the cylinder, two pairs of readings will be obtained for total reflection. In the first set, one-half of the semi-cylinder will act as the collimating lens, the other half acting as the focussing lens : in the next set (when the cylinder is rotated through 180°) the functions of the two halves are exchanged. From the mean of the differences obtained from the two sets of observations, the value of 2 i is obtained with great accuracy, provided the circle is accurately graduated, and the reading Vernier permits of small angular measurements being made.

The circle used in the simple form of apparatus being only divided into degrees, I could not expect to obtain from it, in the ordinary way, any very accurate results; but by using the following method, it was possible to obtain results which are highly accurate.

The platform index is at first clamped down pointing to the zero of the scale, and the circle as a whole rotated till total reflection takes place. The circle is next clamped, and the platform carrying the cylinder unclamped and rotated in the direction of the lower arrow till light is again totally reflected, the

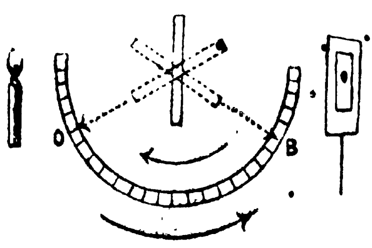


Fig. 15. The dotted lines represent the two positions of the air-film for total reflection.

index reading being now B. The difference of the two readings evidently gives twice the critical angle. The angle is repeated by clamping down the index and rotating the circle as a whole for total reflection in the direction of the upper arrow. The process may thus be repeated, the rotation of the platform in one direction being followed by the rotation of the circle in an opposite direction. There is thus produced at each operation a relative displacement of the index (in reference to the circle) through twice the critical angle. The value of i is by this means obtained with great accuracy, the errors due to eccentricity or defect in graduation being eliminated by repeating the angles n times where $2\,ni$ is as near as possible equal to four right angles or any multiple of four right angles. If R be the difference between the first (zero) and the last readings, the critical angle $i = \frac{R}{2\,n}$. It is evident that by merely increasing n, the value of i could be obtained with any degree of accuracy, even with circles graduated only into degrees.

The index is fixed at the beginning against the zero of scale. It is therefore only necessary to take *one* final reading, and count the number of repetitions. A complete determination could thus be made in the course of a few minutes.

The air-film, as has been said before, should be placed in the vertical plane dividing the cylinder into two halves. This is more easily accomplished by *suspending* a metallic plate on knife edges, from V grooves cut at the ends of a diameter of the upper end of the cylinder. The plate remains vertical under the action of gravity. A central slit is cut in this plate; on opposite sides of this central diaphragm are cemented, as previously stated, the two glass slips which contain the air-film.

One set of readings having been obtained with the semi-cylinder P turned towards the source of light, the cylinder is turned round through 180°, and observation repeated with Q occupying the previous position of P; it will be seen that by this procedure the air-film is also reversed. The mean value of the critical angle obtained from the two sets of observations, one "direct," the other "reverse," is thus free from any outstanding error.

Having explained the principle of measurement, I now proceed to give an account of the experiments, and compare the result obtained by this method with those obtained by previous observers. The values for carbon disulphide, absolute alcohol, glycerine have been determined, but the results obtained by different observers do not agree. The reason for this discrepancy is obvious; it is almost impossible to obtain two different specimens of these substances exactly alike. The only substance which can be obtained in a state of approximate purity is distilled water, but even here we have various contaminations by the absorption of different gases like ammonia and carbonic acid from the atmosphere; or glass itself may be dissolved in minute quantities. The values of the index for water obtained by different observers are therefore not very concordant. The following are the values of the index of water for the D ray :—

Wollaston and Brewster, D ray (temp. not given)	1·336
Sir John Herschel (at density of 1) . .	1·3336

The following are for the D ray at a temperature of 18° :—

Terquem and Trannin	1·3336
Gladstone and Dale (reduced to 18°) . . .	1·3322

If we reject the first two values as somewhat indefinite and take the last two, we find a difference of more than 1 part in a thousand, Gladstone and Dale's result being the lower.

With C ray at the temperature 18° :—

Fraunhofer	1·3317
Gladstone and Dale (reduced to 18°) . . .	1·3304

Here also the same difference is observed. Thus the minimum difference between the best observations is about 1 part in a thousand.

My determinations were made with ordinary distilled water, condensed by passing steam through a coil of copper immersed in cold water. The experiments were carried out with the two following apparatus :—

I. A large circle, roughly graduated into degrees, with a diameter of 45 cm.; the glass trough used is 25 cm. in diameter.

II. The circle was obtained from an old theodolite. The Vernier reads to 1′. The glass cylinder used has a diameter of 14·4 cm.

It must be remarked here that the cylinders at my disposal, though circular in section, were slightly conical in shape. I tried to obviate this defect by using a very small portion of the height of the cylinder for light to pass through, the length of the slit being reduced to about 5 mm.

Just before total reflection, a series of images of the slit are seen reflected by the air-film. When white light is used, and the image is observed through a direct vision spectroscope, interference bands are observed in the spectrum, which flit across it with the slightest rotation of the cylinder.

I give below the results obtained from determinations made on different days (temp. = 26°).

(1) The larger apparatus was used for this experiment (diameter of the cylinder = 25 cm.), and the angle repeated fifteen times.

(2) Experiment with the smaller apparatus (diameter of the cylinder = 14·4 cm.). Reading was only taken of two successive positions for total reflection with the air-film 'direct' and 'reverse.'

(3) The same as above but with a different air-film.

(1) Angle repeated fifteen times.

Direct.	Reverse.
1459°	1460°

$$\text{Mean value for } i = \frac{1459 \cdot 5}{2 \times 15} = 48^\circ\ 39'$$

$$\mu = 1 \cdot 3321.$$

From (2) and (3), mean value of i obtained $= 48^\circ\ 40'$.

$$\mu = 1 \cdot 3317.$$

The values of μ from the best determinations reduced to the temp. 26° are given below :—

Gladstone and Dale	1·3315
Terquem and Trannin	1·3329

The result obtained by me is thus seen to be practically the same as the above.

Having obtained the absolute value of the index of water for the D line and at the temperature of 26°, the following investigations were made to study the effect of different strengths of solution, of temperature, and of different rays in the variation of the index.

It must be remembered that we are concerned here in measurement of effect of small variations from the standard. The absolute value of the index under the changed condition is deduced from the value under standard condition and the small observed variation.

2. Variation of the Index with Different Strengths of Solution

The apparatus is first adjusted for total reflection with distilled water. To the distilled water in the cylinder is added enough salt (*e.g.*, sodium chloride) to make, say, a five per cent. solution. This produces an increase of refractive power, and the angle of incidence has to be decreased to reach the critical angle. The *difference* of the two readings subtracted from the critical angle for distilled water (obtained from a previous accurate determination) gives the critical angle for five per cent. solution, and hence the absolute index. It is to be noticed here that a large number of determinations can be made rapidly by merely adding requisite quantities of salt and taking the corresponding readings.

With a finely-graduated circle, provided with a Vernier, the differences of readings may easily be obtained. With a roughly-graduated scale, the angular differences may be determined by fixing a mirror over the upper portion of the slit, and measuring the small differences in the usual way, by observing a reflected scale through a telescope, or receiving the reflected spot on a scale. A curve of variation of the indices with the different strengths of solution may thus be easily obtained.

3. Effect of temperature

The index of a liquid is increased and the critical angle decreased with the lowering of temperature. Hot water is poured into the cylinder, and the cylinder rotated till the angle of incidence is just a little less than the critical angle for the particular temperature. The liquid is stirred at intervals, and a thermometer bulb placed in the same horizontal layer of the liquid through which light is passing. As the liquid slowly cools down, the critical angle is decreased, and at a certain temperature the image suddenly disappears. The corresponding temperature of the liquid is now observed. The angle is then decreased by a small known amount, and the new temperature for total reflection again observed. In this way the slight variation of the angle with the variation of temperature is found. The absolute value of the critical angle for a standard temperature is known from a previous experiment. Hence the indices for different temperatures may be easily deduced.

4. On the determination of the indices for the different rays and the dispersive power

The value for the D line having been accurately determined by the method of repetition, the values for the other rays are found in the following way :—

Sunlight may be used for the experiment; the image falls on the slit of a direct vision spectroscope. A spectrum is thus formed, in which the well-known Fraunhofer's lines are present. As the cylinder is rotated, a shadow gradually moves along the spectrum, beginning with the most refrangible end. The shadow is made to coincide with the different absorption lines, and the differences between these readings and the "D" reading give the absolute critical angles for the different rays. In this way, the values of the indices for different rays are found, and hence the dispersive power. A greater degree of accuracy is obtained by repeating the difference.

The incandescent filament of a glow lamp may also be used as a source of light. The micrometer in the eye-piece of the spectroscope should have been previously calibrated.

The following determination was made to find the difference between D and F lines. This was repeated ten times, which gave a total difference of 2° 5′. The critical angle for the F ray is therefore less than the angle for D ray by 12·5′. Hence taking the mean critical angle for D to be 48° 39·5′.

μ for D=1·3319.
μ for F =1·3362.

The difference between D and F, as found by me, is therefore about	43 parts in 13,000 at 26°.
Gladstone and Dale found a difference of	42 ,, ,, ,, at 15°.
This difference will, however, be reduced to about . .	41 ,, ,, ,, at 26°.

Indices for solids.—The method for the determination of the indices for solids is precisely the same as that for liquids. The solids are cut in the form of two small semi-cylinders, a process which is not so difficult as the cutting of a prism.

Lecture Demonstration

A few words may now be said about the modification of the above for lecture demonstrations. As only a moderate degree of accuracy is required, the source of light (a slit illuminated with sunlight, or any other powerful source) is brought slightly nearer the cylinder, so that the image is cast on a distant screen.

Effect of temperature.—Half the height of the cylinder is filled with cold liquid a circular piece of mica being placed above. Hot liquid is now slowly and cautiously poured over mica. When the cylinder is rotated, the light from the lower half would be the first to undergo total reflection, and this totally-reflected image may be received on a second suitably-placed screen. Light would, however, be still transmitted through the hot portion of the liquid. There would thus be a transference of one-half of the image from one screen to the other. On further rotation the missing portion would join its other half on the second screen. A slight rotation in one direction or the other would produce corresponding transference of the images from one screen to the other.

Different indices for the different rays.—A spectrum is formed by allowing light which forms the image to pass through a carbon bisulphide prism. As the rotation of the cylinder is continued, different portions of the spectrum would be totally reflected in succession, and would appear on the second screen, the spectra on the two screens being complementary.

Conclusion.—My object has been to get a fairly accurate determination of the index and its variations with an improvised and inexpensive apparatus, which can easily be set up. Even with the simple apparatus described above, the quantitative results obtained were shown to possess great accuracy. The determinations were found to be capable of being made with considerable rapidity. Only one final reading was all that was necessary for the determination of the absolute index. With a finely graduated circle, a true cylinder, and a perfectly parallel air-film, there is no reason why the method described above should not give results possessing the highest degree of accuracy.

(*From unpublished Paper*, 1895.)

VIII

ON THE SELECTIVE CONDUCTIVITY EXHIBITED BY CERTAIN POLARISING SUBSTANCES

In my paper "On the Polarisation of Electric Rays by Double-refracting Crystals" and in a subsequent paper "On a New Electro-Polariscope", I have given accounts of the polarising property of various substances. Amongst the most efficient polarisers may be mentioned nemalite and chrysotile. Nemalite is a fibrous variety of brucite. In its chemical composition it is a hydrate of magnesia, with a small quantity of protoxide of iron and carbonic acid. This substance is found to strongly absorb electric vibrations parallel to its length, and transmit those that are perpendicular to the length. I shall distinguish the two directions as the directions of absorption and transmission. Chrysotile is a fibrous variety of serpentine. In chemical composition it is a hydrous silicate of magnesia. Like nemalite, it also exhibits selective absorption, though not to the same extent. The transmitted vibrations are perpendicular, and those absorbed parallel to the length. Different varieties of these substances exhibit the above property to a greater or less extent. I have recently obtained a specimen of chrysotile with a thickness of only 2·5 cm.; this piece completely polarises the transmitted electric ray by selective absorption.

The action of these substances on the electric ray is thus similar to that of tourmaline on light. It may be mentioned here that I found tourmaline to be an inefficient polariser of the electric ray; it does transmit the ordinary and the extraordinary rays with unequal intensities, but even a considerable thickness of it does not completely absorb one of the two rays.

In Hertz's polarising gratings, electric vibrations are transmitted perpendicular to the wires, the vibrations parallel to the wires being reflected or absorbed. Such gratings would be found to exhibit electric anisotropy, the conductivity in the direction of the wires being very much greater than the conductivity across the wires. The vibrations transmitted through the gratings are thus perpendicular to the direction of maximum conductivity, or parallel to the direction of greatest resistance. The vibration absorbed is parallel to the direction of maximum conductivity.

As the nemalite and chrysotile polarised the electric ray by unequal absorption in the two directions, I was led to investigate whether they, too, exhibited unequal conductivities in the two directions of absorption and transmission.

Nemalite, unfortunately, is difficult to obtain; I have, however, in my possession two specimens of which one is fairly large, and I obtained with it strong polarisation effects. The second piece is not as good as the first, and is rather small. I cut from this latter piece a square of uniform thickness, the adjacent sides of the square being parallel to the directions of transmission and absorption respectively. The resistances of equal lengths in the two directions (with the same cross section) were now measured. The resistance in the direction of transmission was found to be 35,000 megohms, and that in the direction of absorption, only 14,000 megohms.

It will thus be seen that the direction of absorption is also the direction of greatest conductivity, and the direction of transmission is the direction of least conductivity.

My anticipations being thus verified, I proceeded to make further measurements with other specimens. From the perfect specimen of nemalite in my possession, I cut two square pieces, A and B. The size of piece A is 2·56×2·56 cm., with a thickness of 1·1 cm.; B is 2·76×2·76×1·2 cm.

For the determination of resistances I used a sensitive Kelvin galvanometer, having a resistance of 7000 ohms. With three Leclanché cells, 1·4 volt each, and an interposed resistance equivalent to 55,524 megohms, a deflection of 1 division in the scale reading was obtained. The table below gives the results of the measurements which I carried out. They clearly show how the difference of absorption in the two directions is related to the corresponding difference in conductivity.

I then proceeded to make measurements with chrysotile. The specimens I could obtain were not very good. I cut two from the same piece, and a third specimen was obtained from a different variety. The ratios of conductivities found in the three specimens were 1 : 10, 1 : 9, and 1 : 4 respectively. In every case the direction of absorption was found to be the direction of maximum conductivity.

A fibrous variety of gypsum ($CaSO_4$), popularly known as satinspar, also exhibits double absorption; and in this case, too, the conductivity in the direction of absorption is found to be very much greater than in that of transmission.

Specimen A.	Deflections.	Resistance between two opposed faces 2·56×1·1 cm. separated by 2·56 cm.	Ratio of the conductivities.
In the direction of transmission.	26	2136 megohms	1 : 13·8
In the direction of absorption.	360	154 „	

Specimen B.	Deflections.	Resistance between two opposed faces 2·76×1·2 cm. separated by 2·76 cm.	Ratio of the conductivities.
In the direction of transmission.	28	1983 megohms	1 : 13·4
In the direction of absorption.	370	150 „	

One of the strongest polarising substances I have come across is epidote. The crystal I have, is very small in size, and I could not get with it complete absorption of one of the two rays. But it exhibits very strong depolarisation effect, even with a thickness as small as 0·7 cm. This is, undoubtedly, due to strong selective absorption in one direction. I cut a square from this crystal 0·7×0·7 cm. with a thickness of 0·4 cm. Using an E. M. F. of 14 volts the deflections obtained (proportional to the two conductivities) were 105 and 20 divisions respectively. The conductivities in the two directions are, therefore, in the ratio of 5·2 : 1. With an E. M. F. of 100 volts and a diminished sensibility of the galvanometer, the deflections were 205 and 40, the ratio of the conductivities being as 5·1 : 1.

It would thus appear that substances like nemalite which polarise by double absorption, also exhibit double conductivity. It is probable that, owing to this difference of conductivity in the two directions, each thin layer unequally absorbs the incident electric vibrations; and that by the cumulative effect of many such layers, the vibrations which are perpendicular to the direction of maximum conductivity are alone transmitted, the emergent beam being thus completely polarised.

It should, however, be borne in mind that the selective absorption exhibited by a substance depends, also on the vibration frequency of the incident radiation. I have drawn attention to the peculiarity of tourmaline which does not exhibit double absorption of the electric ray to a very great extent. The specimen I experimented with is, however, one of a black variety of tourmaline, and not of the semi-transparent kind generally used for optical work.

Though the experiments already described are not sufficiently numerous for drawing a general conclusion as to the connection between double absorption attended, with polarisation, and double conductivity, there is, however, a large number of experiments I have carried out which seem to show that a double-conducting structure does, as a rule, exhibit double absorption and consequent polarisation. Out of these experiments I shall here mention one which may prove interesting. Observing that an ordinary book is unequally conducting in the two directions—parallel to and across the pages—I interposed it, with its edge at 45°, between the crossed polariser and analyser of an electro-polariscope. The extinguished field of radiation was immediately restored. I then arranged both the polariser and the analyser vertical and parallel, and interposed the book with its edge parallel to the direction of electric vibration. The radiation was found completely absorbed by the book, and there was not the slightest action on the receiver. On holding the book with its edge at right angles to the electric vibration, the electric ray was found copiously transmitted. An ordinary book would thus serve as a perfect polariser of the electric ray. The vibrations parallel to the pages are completely absorbed, and those at right angles transmitted in a perfectly polarised condition.

(*Proc. Roy. Soc., Jan.* 1897.)

IX

ELECTRO-MAGNETIC RADIATION AND THE POLARISATION OF THE ELECTRIC RAY

The work of Hertz in verifying the anticipations of Maxwell has been followed in this country by many important investigations on Electric Waves. The Royal Institution witnessed the repetition of some of the brilliant experiments of Professors Fitzgerald and Lodge. I am glad to have an opportunity to lay before you, at this very same place, an account of some work which I carried out in India.

As the subject of ether waves produced by periodic electric disturbances is to be dealt with in this lecture, a few models exhibiting the production of material waves by periodic mechanical disturbances may be of interest. A pendulum swings backwards and forwards at regular intervals of time; so does an elastic spring when bent and suddenly released. These periodic strokes produce waves in the surrounding medium; the aerial waves striking the ear may, under certain conditions, produce the sensation of sound. The necessary condition for audibility is, that the frequency of vibration should lie within certain limits.

As the air is invisible, we cannot see the waves that are produced. Here is a model in which the medium is thrown into visible waves by the action of periodic disturbances. The beaded string representing the medium is connected at its lower end with a revolving electric motor. The rotation of the motor is periodic; observe how the periodic rotation throws the string

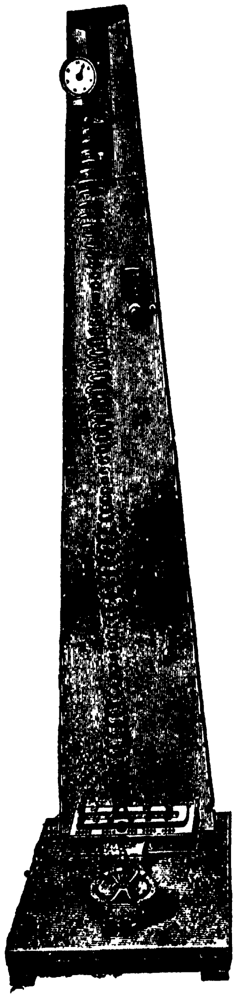


Fig. 16. Mechanical Wave Apparatus.
(The current regulating the speed of rotation is varied by an interposed rheostat. The counter is at the top.)

into waves; how these waves carry energy from the source to a distant place; how a suitable receiver, a bell for example, is made to respond at the distant end. I now produce a quicker rotation by sending a stronger current through the motor; the frequency or pitch is raised, and the waves formed are seen to become shorter. The different frequencies are determined by means of the attached counter.

Here is a second model, a spiral spring, attached to which is a thin string. As the string is pulled, the spring is strained more and more, till the thread breaks. The spring, suddenly released, is seen to oscillate up and down. Electric vibration is produced in a somewhat similar way. If two metallic spheres be strongly charged with opposite electrifications, the medium is electrically strained, and when this strain is suddenly removed by a discharge, waves are produced in the medium.

The discharge is oscillatory, consisting of backward and forward rushes of electricity; positive electricity flowing now in one direction, and immediately afterwards in an opposite direction.

For the production of oscillatory discharge, Hertz used plates or rods with sparking balls at the ends. He found that the sparks ceased to be oscillatory as soon as the surface of the sparking balls became roughened; there was then a leak of electricity, and no sudden discharge. The balls had to be taken out every now and then for repolishing, and the process was tedious in the extreme. Prof. Lodge made the important discovery that if two side balls were made to spark into an interposed third ball, the oscillatory nature of the discharge was not affected to so great an extent by a change in the nature of the surface. But even here the disintegration of the sparking surface produced by a torrent of sparks soon puts an end to oscillation. I found this difficulty removed by making the balls of platinum, which resists the disintegrating action. I also found that it was not at all necessary to have a series of useless sparks, which ultimately spoils the efficiency of the radiator and makes its action uncertain. A flash of radiation for an experiment is obtained from a single spark, and for a series of experiments one does not require more than fifty or a hundred sparks, which do not in any way affect the radiator. As an electric generator I use a small and modified form of Ruhmkorff's coil, actuated by a single storage cell. A spark is produced by a short contact and subsequent break of a tapping key. With these modifications one of the most troublesome sources of uncertainty is removed. The coil and the cell are enclosed in a small double-walled metallic box, with a tube for the passage of the electric beam. The magnetic variation due to the make and break of the primary of the Ruhmkorff's coil, disturbs the receiver. This difficulty is removed by making the inner box of soft iron which acts as a magnetic screen.

A few words may here be said about the necessary conditions to be kept in view in making an electric wave apparatus an instrument of precision. If one merely wishes to produce response in a receiver at a distance, the more energetic the vibration is, the more likely it is to overcome obstacles. The waves may with advantage be of large size, as they possess very great penetrative power. The surface or the depth of the sensitive layer in the receiver may be extended, for if one part of it does not respond another part will. But for electro-optical investigations the conditions to be fulfilled are quite different. Too great an intensity of radiation makes it almost impossible to prevent the disturbance due to stray radiation. As the waves are invisible, it is difficult to know through what unguarded points they are escaping. They may be reflected by the walls of the room or even by the person of the experimenter, and falling on the receiver disturb it.

The radiation falling on any portion of the receiving circuit, the leading wires or the galvanometer, disturbs the sensitive receiver. It is extremely difficult to shield the receiving circuit from the disturbing action of stray radiation. All difficulties were, however, successfully removed by the use of short electric waves. With these, it is not at all necessary to take special precautions to shield either the galvanometer or the leading wires, the sensitive layer in the receiver alone being affected by the radiation. The bare leading wires may be exposed in close proximity to the source of radiation, and yet no disturbance is produced.

For experimental investigations it is also necessary to have a narrow pencil of electric radiation, and this is very difficult to obtain, unless waves of very short length are used. With large waves diverging in all directions and curling round corners, all attempt at accurate work is futile. For angular measurements it is necessary to direct the electric beam in the given direction along narrow tubes, and receive it in another tube in which is placed the receiver. The waves experience great difficulty in passing through narrow apertures, and there are other troubles arising from the interference of direct and reflected waves. All these drawbacks were ultimately removed by making suitable radiators emitting very short waves; the three radiators here exhibited, give rise to waves which are approximately $\frac{1}{4}$ inch, $\frac{1}{2}$ inch and 1 inch in length. The intensity of emitted radiation is moderately strong, and this is an advantage in many cases. It sometimes becomes necessary to have a greater intensity without the attendant trouble inseparable from too long waves. I have been able to secure this by making a radiator, where the oscillatory discharge takes place between two hollow hemispheres and an interposed platinum ball. The intensity of radiation is by this expedient very greatly increased. The parallel pencil of electric radiation, used in many of the experiments to be described below, is only about one cm. in diameter. The production of such a narrow pencil became absolutely necessary for a certain class of investigations. Merely qualitative results for reflection or refraction may no doubt be obtained with gigantic mirrors or prisms, but when we come to study the phenomena of polarisation as exhibited by crystals, Nature imposes a limit, and this limitation of the size of the crystals has to be accepted in conducting any investigation on their polarising properties.

The greatest drawback, however, in conducting experimental investigations on the optical properties of electric radiation arises from the difficulty of constructing a satisfactory receiver for detecting the radiation. For this purpose I at first used the original form of coherer made of metallic filings as devised by Professor Lodge. It is a very sensitive detector for electric radiation, but unfortunately its indications are often extremely capricious.

The conditions for a satisfactory receiver are the following :—

(1) Its indications should always be reliable.

(2) Its sensitiveness should remain fairly uniform during the course of the experiment.

(3) The sensibility should be capable of variation, to suit different experiments.

(4) The receiver should be of small size, and preferably linear, for accurate angular measurements.

These conditions seemed at first almost impossible to attain; the coherer sometimes would be so abnormally sensitive that it would react without any apparent cause. At other times, when acting in an admirable manner, the sensitiveness would suddenly disappear at the most tantalising moment. It was a dreary experience when the radiator and the receiver failed by turns, and it was impossible to find out which was really at fault.

From a series of experiments carried out to find the causes of the erratic behaviour of the receiver, I was led to suppose that the uncertainty in its response is probably due to the following :—

(1) Some of the particles of the coherer might be in too loose a contact against each other; whereas others might be jammed together, preventing proper response.

(2) The loss of sensibility might also be due to the fatigue produced on the contact surfaces by the prolonged action of radiation.

(3) Since the radiation was almost entirely absorbed by the outermost layer, the inner mass, which acted as a short circuit, was not merely useless but might introduce complications.

For these reasons I modified the receiver into a spiral-spring form. Fine metallic wires (generally steel, occasionally others, or a combination of different metals) were wound in narrow spirals and laid in a single layer on a groove cut in ebonite, so that the spirals could roll on a smooth surface. The spirals are prevented from falling by a glass slide in front. The ridges of the contiguous spirals made numerous and well-defined contacts, about one thousand in number. The useless conducting mass was thus abolished, and the resistance of the receiving circuit almost entirely concentrated at the sensitive contact surface exposed to radiation. If any change of resistance, however slight, took place at the sensitive layers, the galvanometer in circuit would show strong indications. The pressure throughout the mass was made uniform as each spring transmitted the pressure to the next. When the contact surfaces had too long been acted on, fresh surfaces could easily be brought into operation by the simultaneous rolling of all the spirals.

The sensibility of the receiver to the radiation, I found, depends (1) on the pressure to which the spirals are subjected, and (2) on the E. M. F. acting on the circuit. The pressure on the spirals may be adjusted, as will be described later on, by means of a fine screw. The E. M. F. is varied by a potentiometer-slide arrangement. This is a matter of great importance, as I often found a receiver, otherwise in good condition, failing to respond when the E. M. F. varied slightly from the proper value. The receiver, when subjected to long-continued radiation, undergoes exhaustion. The sensibility can, however, be maintained fairly uniform by slightly varying the E. M. F. to keep pace with the fatigue produced.

The receiving circuit thus consists of a spiral-spring coherer, in series with a voltaic cell and a dead-beat galvanometer. The spirals are placed between two pieces of brass, of which the upper one is sliding and the lower one fixed. These two pieces are in connection with two projecting metallic rods, which serve as electrodes. An electric current enters along the breadth of the top spiral and leaves by the lowest spiral, having to traverse the intermediate spirals along the numerous points of contact. When electric radiation is absorbed by the sensitive surface, there is a sudden diminution of the resistance, and the galvanometer spot is violently deflected.

By means of a very fine screw the upper sliding piece can be gently adjusted in or out. The spirals can thus be very gradually compressed, and the resistance of the receiver diminished. The galvanometer spot can thus easily be brought to any convenient position on the scale. When electric radiation falls on the sensitive surface the spot is suddenly deflected.

The receiver thus constructed is perfectly reliable; the sensibility can be widely varied to suit different experiments, and this sensibility can be maintained fairly uniform. The sensitiveness, when necessary, can be exalted to almost any extent, and it is thus possible to carry out some of the most delicate experiments (specially on polarisation) with certainty. In my more recent apparatus I use a single-contact receiver made of steel, nickel, aluminium or magnesium. These receivers can not only be made extremely sensitive, but also highly reliable.

The main difficulties having been thus removed, I attempted to construct a portable apparatus, with which all the experiments on electric radiation could be carried out with almost as great an ease and certainty as corresponding experiments on light, and with which even quantitative results could be obtained with fair accuracy.

The complete apparatus is here exhibited; all its different parts, including the galvanometer, and all the accessories for reflection, refraction, polarisation, and other experiments, are contained in a small case only 60 cm. in length, 30 cm. in height and 30 cm. in breadth. The apparatus can be set up and various adjustments made in the course of a few minutes.

The radiating apparatus is 15×12×7 cm., the size of a small lantern. It contains the coil and a small storage cell; the radiator tube is closed with a thin plate of ebonite to prevent deposit of dust on the radiator. One charge of the cell stores enough energy for numerous experiments. It is always ready for use and requires very little attention. A flash of radiation for an experiment is produced by a single tap and break of the interrupting key.

The radiating apparatus and the receiver are mounted on stands sliding on an optical bench. Experiments are carried out with divergent or parallel beams of electric radiation. To obtain a parallel beam, a lens of sulphur or glass is mounted in a tube. Suitable lenses can be constructed from the accurate determination, which I have been able to make, of the indices of refraction of various substances for the electric ray, by a method which will be described later on. This lens-tube fits on the radiator-tube, and is stopped by a guide when the oscillatory spark is at the principal focus of the lens. The radiator-tube is further provided with a series of diaphragms by which the amount of radiation can be varied.

For experiments requiring angular measurement, a spectrometer-circle is mounted on one of the sliding stands. The spectrometer carries a circular platform, on which the various reflectors and refractors are placed. The platform carries an index, and can rotate independently of the circle on which it is mounted. The receiver is carried on a radial arm (provided with an index), and points to the centre of the circle.

I shall now exhibit some of the principal experiments on electric radiation.

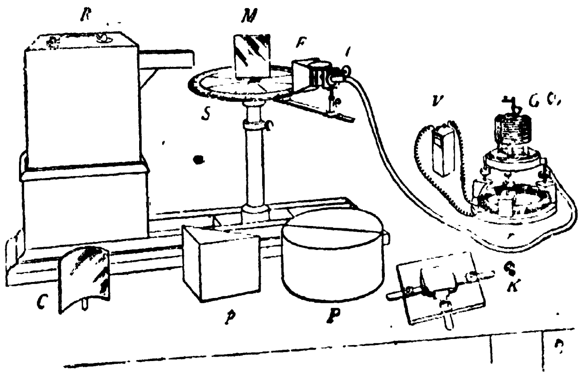


Fig. 17. Arrangement of the Apparatus. One-sixth nat. size.

R, radiator ; S, spectrometer-circle ; M, plane mirror ; C, cylindrical mirror ; *p*, totally reflecting prism ; P, semi-cylinders ; K, crystal-holder ; F, collecting funnel attached to the spiral spring receiver ; *t*, tangent screw, by which the receiver is rotated ; V, voltaic cell ; *r*, circular rheostat ; G, galvanometer.

Selective Absorption

I arrange the radiation apparatus so that a parallel beam of electric radiation proceeding from the lantern falls on the receiver placed opposite ; the receiver responds energetically, the light-spot from the galvanometer being swept violently across the screen. I now interpose various substances to find out which of them allow the radiation to pass through and which do not. A picee of brick, or a block of pitch, is thus seen to be very transparent, whereas a thick stratum of water is quite opaque. A substance is said to be coloured when it allows light of one kind to pass through, but absorbs light of a different kind. A block of pitch is opaque to visible light, but transparent to electric radiation; whereas water, which is transparent to light, is opaque to electric radiation. These substances exhibit selective absorption, and are therefore coloured.

There is an interesting speculation in reference to the possibility of the sun emitting electric radiation. No such radiation has yet been detected in sunlight. It may be that the electric rays are absorbed by the solar or the terrestrial atmosphere. As regards the latter supposition, the experiment which I am able to exhibit on the transparency of liquid air may be of interest. Professor Dewar has kindly lent me this large bulb full of liquid air, which is equivalent to a great thickness of ordinary air. This thick stratum allows the radiation to pass through with the greatest facility, proving the high transparency of the liquid air.

Verification of the Laws of Reflection

A small plane metallic mirror is mounted on the platform of the spectrometer-circle. The receiver is mounted on a radial arm. The law of reflection is easily verified in the usual way. The second mirror, which is curved, forms an invisible image of the source of radiation. As I slowly rotate the cylindrical mirror, the invisible image moves through space; now it falls on the receiver, and there is a strong response produced in the receiver.

Refraction

Deviation of the electric ray can be easily shown by a prism made of sulphur or ebonite. More interesting is the phenomenon of total reflection. A pair of totally-reflecting prisms may be obtained by cutting a cube of glass, which may be an ordinary paper-weight, across a diagonal. The critical angle of a specimen of glass I found to be 29°, and a right-angled isosceles prism of this material produces total reflection in a very efficient manner. When the receiver is placed opposite the radiator, and the prism interposed with one of its faces perpendicular to the electric beam, there is not the slightest action on the receiver. On turning the receiver through 90°, the receiver responds to the totally-reflected ray.

Opacity due to multiple refraction and reflection, analogous to the opacity of powdered glass to light, is shown by filling a long trough with irregularly-shaped pieces of pitch, and interposing it between the radiator and the receiver. The electric ray is unable to pass through the heterogeneous media, owing to the multiplicity of refractions and reflections, and the receiver remains unaffected. But on restoring partial homogeneity by pouring in kerosene, which has about the same refractive index as pitch, the radiation is easily transmitted.

Determination of the Index of Refraction

Accurate determination of the indices of refraction becomes important when lenses have to be constructed for rendering the electric beam parallel. The index for electric radiation is often very different from the optical index, and the focal distance of a glass lens for light gives no clue to its focal distance for electric radiation. I found, for example, the index of refraction of a specimen of glass to be 2·04, whereas the index of the same specimen for sodium light is only 1·53.

There are again many substances, like the various rocks, wood, coal-tar, and others, whose indices cannot be determined owing to their opacity to light. These substances are, however, transparent to electric radiation, and it is therefore possible to determine their electric indices. The prism-method is unsuitable for accurate determination of the index. Very good results are obtained by the following method, of which I shall exhibit the optical counterpart. When light passes from a dense into a light medium, then, at a certain critical angle, the light is totally reflected, and from the critical angle the index can be determined. I have here a cylindrical trough filled with water. Two glass plates enclosing a parallel air-film are suspended vertically across the diameter of the cylinder, dividing the cylinder into two halves. The cylinder, mounted on a graduated circle, is adjusted in front of an illuminated slit, an image of the slit being cast by the water-cylinder on the screen. The divergent beam from the slit, rendered nearly parallel by the first half of the cylinder, is incident on the air-film, and is then focussed by the second half of the cylinder. As the cylinder is slowly rotated, the angle of incidence at the air-film is gradually increased, but the image on the screen remains fixed. On continuing the rotation you observe the almost sudden extinction of the image. I say almost, because the light is not monochromatic, and the different components of white light undergo total reflection in succession. Just before total extinction the image you observe is reddish in colour, the violet and the blue lights having been already reflected. On continuing the rotation the image is completely extinguished. Rotation of the cylinder in an opposite direction gives another reading for total reflection, and the difference of the two readings is evidently equal to twice the critical angle.

In a similar way I have been able to determine the indices of refraction of various substances, both solid and liquid, for electric radiation. In the case of solids, two semi-cylinders, separated by a suitable parallel air-space, are placed on the spectrometer-circle, the receiver being placed opposite the radiator. The trouble of following the deviated ray is obviated, and the critical angle determined with considerable accuracy. The index of refraction of glass thus found is 2·04; that of commercial sulphur, 1·73.

Double Refraction and Polarisation

I now proceed to demonstrate some of the principal phenomena of polarisation, especially in reference to the polarisation produced by crystals and other substances, and by solid dielectrics when subjected to strain due to pressure or unequal heating.

As the wave-length of electric radiation is many thousand times the wave-length of light, there is a

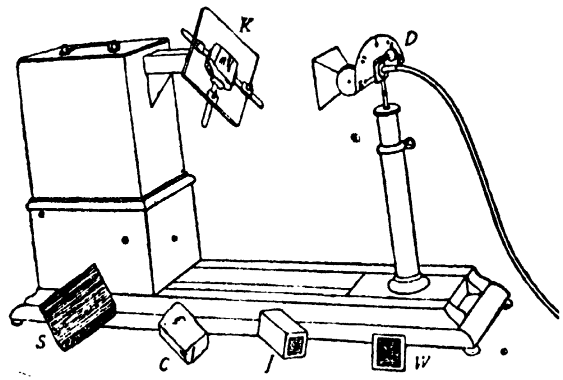


Fig. 18. Polarisation Apparatus.

K, crystal-holder; S, a piece of stratified rock; C, a crystal; J, jute polariser; W, wire-grating polariser; D, vertical graduated disc, by which the rotation is measured.

misgiving as to whether it would be possible to exhibit polarisation effects with crystals of ordinary size. I shall demonstrate that such a misgiving is groundless.

A beam of ordinary light incident on a crystal of Iceland spar is generally bifurcated after transmission, and the two emergent beams are found polarised in planes at right angles to each other. The usual optical method of detecting the bi-refringent action of crystal, is to interpose it between the crossed polariser and analyser. The interposition of the crystal at the proper angle brightens the dark field. This is the so-called depolarisation effect, and is a delicate test for double-refracting substances. There is, however, no depolarisation when the principal plane of the crystal coincides with the polarisation planes of either the polariser or the analyser. The field also remains dark when the optic axis of the crystal is parallel to the incident ray.

A similar method is adopted for experimenting with polarised electric radiation.

The spectrometer-circle is removed from the optical bench, and an ordinary stand for mounting the receiver substituted. By fitting the lens-tube, the electric beam is made parallel. At the end of the tube may be fixed either the grating polariser or the jute or serpentine polarisers, to be presently described.

The receiver fitted with the analyser is adjusted by a tangent screw, the rotation of the analyser being measured by means of an index and a graduated vertical disc.

The polarising gratings may be made, according to Hertz, by winding copper wires, parallel, round square frames. The polarisation apparatus is, however, so extremely delicate, that unless all the wires are strictly parallel, and the gratings *exactly* crossed, there is always a resolved component of radiation which acts on the sensitive receiver. It is very difficult to secure the exact crossing of the gratings. I have found it to be a better plan to take two thick square plates of copper of the same size, and, placing one over the other, cut series of slits (which stop short of the edges) parallel to one of the edges. One of these square pieces serves as a polariser, and the other as an analyser. When the two square pieces are adjusted, face to face, with coincident edges, the gratings must either be parallel or exactly crossed. Such accurate adjustments make it possible to carry out some of the most delicate experiments.

The radiator-tube, with the lens and the attached polariser, is capable of rotation. The emergent beam may thus be polarised in a vertical or a horizontal plane. The analyser fitted on to the receiver may also be rotated. The gratings may thus be adjusted in two positions.

(1) Parallel position.

(2) Crossed position.

In the first position the radiation transmitted through both the gratings, falls on the sensitive surface, and the galvanometer responds. The field is then said to be bright. In the second position the radiation is extinguished by the crossed gratings, the galvanometer remains unaffected, and the field is said to be dark. But the field is restored on interposition of a double-refracting substance in certain positions between the crossed gratings, and the galvanometer-spot sweeps across the scale.

The analyser and the polariser are now exactly crossed, and there is not the slightest action on the receiver. The polariser is now slightly displaced from the crossed position, and the galvanometer-spot is seen to be violently deflected.

The gratings are once more adjusted in a crossed position. I have in my hand a large block of the crystal beryl which is perfectly opaque to light. I now hold the crystal with its principal plane inclined at 45° between the crossed gratings, and the galvanometer-spot, hitherto quiescent, sweeps across the scale. It is very curious to observe the restoration of the extinguished field of electric radiation, itself invisible, by the interposition of what appears to the eye to be a perfectly opaque block of crystal. If the crystal is slowly rotated, there is no action on the receiver when the principal plane of the crystal is parallel to either the polariser or the analyser. Thus, during one complete rotation there are four positions of the crystal when no depolarisation effect is produced.

Rotation of the crystal, when held with its optic axis parallel to the incident ray, produces no action. The field remains dark.

Here is another large crystal, idocrase, belonging to the orthorhombic system, which shows the same action. It is not at all necessary to have large crystals; a piece of calc-spar, taken out of an optical instrument, will be found effective in polarising the electric ray. The effect produced by the crystal epidote is, however, extraordinary. I have here a piece with a thickness of only ·7 cm., smaller than a single wave-length of electric radiation, and yet observe how strong is its depolarising effect.

I subjoin a representative list of crystals belonging to the different systems, which would be found to produce double refraction of the electric ray.

Tetragonal System.—Idocrase, scapolite.

Orthorhombic System.—Barytes, celestine, cryolite, andalusite, hypersthene.

Hexagonal System.—Calcite, apatite, quartz, beryl, tourmaline.

Monoclinic System.—Selenite, orthoclase, epidote.

Triclinic System.—Labradorite, microcline, amblygonite.

Double Refraction produced by a Strained Dielectric

Effect due to Pressure.—A piece of glass, when strongly compressed, becomes double refracting for light. An analogous experiment may be shown with electric radiation. Here is a piece of slate which from the nature of its formation had been subjected to great pressure. I interpose this piece with the plane of stratification inclined at 45°, and the spot of light flies off the scale. I now carefully rotate the piece of slate; there is no depolarisation effect when the plane of stratification is parallel to either the polariser or the analyser. Thus the existence of strain inside an opaque mass can easily be detected, and what is more, the directions of maximum and minimum pressures can be determined with great exactitude.

An effect similar to that produced by unannealed glass may be shown by this piece of solid paraffin, which was cast in a mould, and chilled unequally by a freezing mixture. One of these blocks was cast two years ago, and it has still retained its unannealed property. This effect may even be shown without any special preparation. Pieces of glass or ebonite, too, are often found sufficiently strained to exhibit double refraction of the electric ray.

Phenomena of Double Absorption

In search of a crystal polariser, I naturally turned to tourmaline, but was disappointed to find it utterly unsuitable as a polariser. There is a difference in transparency in directions parallel and perpendicular to the length, but even a considerable thickness of the crystal did not completely absorb one of the two rays. Because tourmaline polarises visible light by selective absorption, it does not follow that all kinds of radiation would be so polarised.

It was a long time before I could discover crystals which acted as electric tourmalines. In the meanwhile I found many natural substances which produced polarisation by selective unilateral absorption. For example, I found locks of human hair to polarise the electric ray. I have here two bundles of hair; I interpose one at 45°, and you observe the depolarisation effect. The darker specimen seems to be the more efficient. Turning to other substances more easily accessible, I found vegetable fibres to be good polarisers. Among these may be mentioned the fibres of aloes (*Agave*), rhea (*Boehmeria nivea*), pine-apple (*Ananas sativus*), plantain (*Musa paradisiaca*). Common jute (*Corchorus capsularis*) exhibits the property of polarisation in a very marked degree. I cut fibres of this material about 3 cm. in length, and built with them a cell with all the fibres parallel. I subjected this cell to a strong pressure under a press. I thus obtained a compact cell 3 cm. by 3 cm. in area, and 5 cm. in thickness.

This was mounted in a metallic case, with two openings 2 cm. by 2 cm. on opposite sides for the passage of radiation. This cell absorbs vibrations parallel to the length of the fibres, and transmits those perpendicular to the length. Two such cells could thus be used, one as a polariser and the other as an analyser.

Turning to crystals I found a large number of them exhibiting selective absorption in one direction. Of these nemalite and chrysotile exhibit this property to a remarkable extent. Nemalite is a fibrous variety of brucite, chrysotile being a variety of serpentine. The direction of absorption in these cases is parallel to the length, the direction of transmission being perpendicular to the length. I have here a piece of chrysotile, only one inch in thickness. I adjust the polariser and the analyser parallel, and interpose the chrysotile with its length parallel to the electric vibration. You observe that the radiation is completely absorbed, none being transmitted. I now hold the piece with its length perpendicular to the electric vibration; the radiation is now copiously transmitted. Chrysotile is thus seen to act as a perfect electric tourmaline.

Anisotropic Conductivity exhibited by certain Polarising Substances

In a polarising grating, the electric vibrations perpendicular to the bars of the grating are alone transmitted, the vibrations parallel to the grating being absorbed or reflected. In a grating we have a structure which is not isotropic, for the electric conductivity parallel to the bars is very great, whereas the conductivity across the bars (owing to the interruptions due to spaces) is practically zero. We may, therefore, expect electric vibrations parallel to the bars to produce local induction currents, which would ultimately be dissipated as heat. There would thus be no transmission of vibrations parallel to the grating, all such vibrations being absorbed. But owing to the break of metallic continuity, no induction current can take place across the grating; the vibrations in this direction are, therefore, transmitted. From these considerations it is seen how non-polarised vibrations falling on a grating would have the vibration components parallel to the direction of maximum conductivity absorbed, and those in the direction of least conductivity transmitted in a polarised condition.

I have shown that nemalite and chrysotile polarise by selective absorption, the vibration perpendicular to their length being transmitted, and those parallel to their length being absorbed. Bearing in mind the relation between the double conductivity and double absorption, as exhibited by gratings, I was led to investigate whether the directions of the greatest and least absorptions in nemalite and chrysotile were also the directions of maximum and minimum conductivities respectively. I found the conductivity of a specimen of nemalite in the direction of absorption to be about fourteen times the conductivity in the direction of transmission. In chrysotile, too, the directions of the greatest and least absorption were also the directions of maximum and minimum conductivities.

It must, however, be noted that the substances mentioned above are bad conductors, and the difference of conductivity in the two directions is not anything like what we get in polarising gratings. A thin layer of nemalite or chrysotile will, therefore, be unable to produce complete polarisation. But by the cumulative effect of many such layers in a thick piece, the vibrations which are perpendicular to the direction of maximum conductivity are alone transmitted, the emergent beam being thus completely polarised.

A double-conducting structure will thus be seen to act as a polariser. I have here an artificial electric tourmaline, made of a bundle of parallel capillary glass fibres. The capillaries have been filled with dilute copper sulphate solution.

A simple, and certainly the most handy, polariser is one's outstretched fingers. I interpose my fingers at 45° between the crossed polariser and the analyser, and you observe the immediate restoration of the extinguished field of radiation.

While repeating these experiments I happened to have by me this old copy of 'Bradshaw', and it occurred to me that here was an excellent double-conducting structure which ought to polarise the electric ray. For looking at the edge of the book we see the paper continuous in one direction along the pages, whereas this continuity is broken across the pages by the interposed air-films. I shall now demonstrate the extraordinary efficiency of this book as an electric polariser. I hold it at 45° between the crossed gratings, and you observe the strong depolarisation effect produced. I now arrange the polariser and the analyser in a parallel position, and interpose the 'Bradshaw' with its edge parallel to the electric vibration; there is not the slightest action in the receiver, the book held in this particular direction being perfectly opaque to electric radiation. But on turning it round through 90°, the 'Bradshaw', usually so opaque, becomes quite transparent, as is indicated by the violent deflection of the galvanometer-spot of light. An ordinary book is thus seen to act as a perfect polariser of the electric ray; the vibrations parallel to the pages are completely absorbed, and those at right angles transmitted in a perfectly polarised condition.

The electric radiation is thus seen to be reflected, refracted and polarised just in the same way as light is reflected, refracted and polarised. The two phenomena are identical.

By pressing the key of this radiation apparatus I am able to produce ether vibrations 30,000 millions in one second. A second stop in connection with another apparatus will give rise to a different vibration. Imagine a large electric organ provided with a very large number of stops, each key giving rise to a particular ether note. Imagine the lowest key producing one vibration in a second. We should then get a gigantic ether wave 186,000 miles long. Let the next key give rise to two vibrations in a second, and let each succeeding key produce higher and higher notes. Imagine an unseen hand pressing the different keys in rapid succession. The ether notes will thus rise in frequency from one vibration in a second, to tens, to hundreds, to thousands, to hundreds of thousands, to millions, to millions of millions. While the ethereal sea in which we are all immersed is being thus agitated by these multitudinous waves, we shall remain entirely unaffected, for we possess no organs of perception to respond to these waves. As the ether note rises still higher in pitch, we shall for a brief moment perceive a sensation of warmth. As the note still rises higher, our eye will begin to be affected, a red glimmer of light will be the first to make its appearance. From this point the few colours we see are comprised within a single octave of vibration, from about 400 to 800 billions in one second. As the frequency of vibration rises still higher, our organs of perception fail us completely; a great gap in our consciousness obliterates the rest. The brief flash of light is succeeded by unbroken darkness.

These great regions of invisible lights are now being slowly and patiently explored. In time the great gaps which now exist will be filled up, and light-gleams, visible and invisible, will be found merging one into the other in unbroken sequence.

Before concluding I take this opportunity of expressing my sincere thanks to the Managers of the Royal Institution for according me the privilege of addressing you this evening. The land from which I come did at one time strive to extend human knowledge, but that was many centuries ago. It is now the privilege of the West to lead in this work. I would fain hope, and I am sure I am echoing your sentiments, that a time may come when the East, too, will take her part in this glorious undertaking; and that at no distant time it shall neither be the West nor the East, but both the East and the West, that will work together, each taking her share in extending the boundaries of knowledge, and bringing out the manifold blessings that follow in its train.

(Friday Evening Discourse, Royal Institution, Jan. 1897.)

X

THE ROTATION OF PLANE OF POLARISATION OF ELECTRIC WAVES BY A TWISTED STRUCTURE

In my previous papers I have given accounts of the double refraction and polarisation of electric waves produced by various crystals and other substances, and also by strained dielectrics. An account was there given of the polarisation apparatus with which the effects were studied. In the present investigation effects had to be studied which were exceedingly feeble. The apparatus had, therefore, to be made of extreme sensitiveness; but the secondary disturbances became at the same time more pronounced, and the great difficulty experienced was in avoiding them.

In one of my communications I alluded to the fact that the secondary disturbances are to a great extent reduced when the radiators are made small. The advantage of a large radiator is the comparative ease with which the receiver can be adjusted to respond to the waves, but this advantage is more than counterbalanced by the increased difficulty with the stray radiation and other disturbances. On the other hand, with small radiators, the difficulty is in the proper adjustment of the receiver. It then becomes necessary to have very exact adjustments of the receiver, both as regards the pressure to which the sensitive spirals are subjected and the E. M. F. acting on the circuit. It is only after some practice that the peculiarity of each receiver is properly understood, when it becomes easy to make the necessary adjustments by which the receiver becomes quite certain in action. For various reasons the radiation emitted by small radiators are more favourable for accurate work.

In order that the surface of the radiator should be little affected by the disintegrating action of the sparks, I use a single spark for producing a flash of radiation. There used to be, however, some uncertainty from a discharge occasionally failing to be oscillatory. The cause of this uncertainty is ascribed to the deposit of dust on the sparking surface. For greater certainty of action some observers immerse the radiator in oil. The use of oil is under any circumstances troublesome. This is specially so in polarisation experiments, when the radiator has to be placed in different azimuths. I have for these reasons avoided the oil-immersion arrangement, and have tried to secure certainty of oscillatory discharge without this expedient. Attention was specially paid to the coil and the primary break. A radiator has also been constructed which is found to be extremely efficient. It consists of two platinum beads, each 2 mm. in diameter, separated by 0·3 mm. spark-gap. There is no interposed third ball. This radiator, though kept exposed for days without any protecting cover, was yet found to give rise to a succession of effective discharges without a single failure. I even went so far as to pour a stream of dust on the radiator; in spite of this severe treatment, the sparks were found to be quite effective in giving rise to electric oscillation.

The receiver, too, is perfectly certain in its action, and various degrees of sensitiveness may be given to it. In the following experiments, the sensitiveness had to be very greatly enhanced, and this, as alluded to above, was secured by proper adjustments. The secondary disturbances were got rid of by careful screening. But one serious difficulty was encountered at the very outset, in the failure of the polariser to produce *complete* polarisation. In my first experiments on polarisation (the receiver then used not having been very sensitive), polarisers made of wire gratings were found effective. But in my later experiments with still more sensitive receivers, I found that, owing probably to the want of strict parallelism of the wires and the difficulty of *exactly* crossing the analyser and polariser, it was impossible to produce total extinction of the field. I then made a polariser and analyser by cutting parallel slits out of two square pieces of thick copper. When the square pieces were adjusted with coincident edges, the analyser and polariser were either exactly parallel or exactly crossed. This improvement enabled me to carry out successfully some of the more delicate experiments. In the present course of investigation the sensitiveness of the receiver had to be raised to a still higher degree, and it was found that the polariser hitherto found efficient failed to produce complete polarisation, so that even when the polariser and the analyser were exactly crossed the non-polarised portion of radiation was of sufficient intensity to produce strong action on the receiver.

In the paper "On the Selective Conductivity exhibited by some Polarising Substances" I described a book-form of polariser, when an ordinary book was shown to produce polarisation of the transmitted beam, the vibrations parallel to the pages being absorbed, and those at right angles transmitted in a polarised condition. The advantage of this form of polariser was that the extent to which the rays were polarised depends on the thickness of the polarising medium. The rays could thus be completely polarised by giving the medium a sufficient thickness, this thickness being determined by the intensity of the radiation used and the sensitiveness of the receiver. The necessary thickness of the book-polariser can be materially decreased by making the book consist of alternate leaves of paper and tinfoil. The book was then strongly compressed, and blocks of suitable size cut out to form the polariser and the analyser. Each of these blocks is then enclosed in a brass cell, with two circular openings on opposite sides for the passage of radiation. The size of the polariser I use is 6×6 cm., with a thickness of 4·5 cm.; the aperture is 4 cm. in diameter. These polarising cells I find to be quite efficient; when two such cells are crossed, the field is completely extinguished.

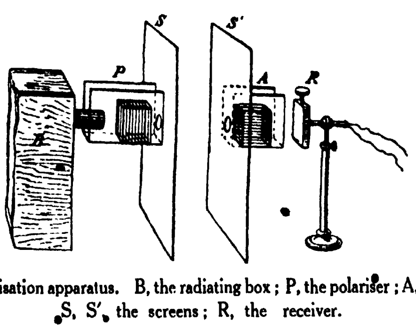


Fig. 19. Polarisation apparatus. B, the radiating box; P, the polariser; A, the analyser; S, S', the screens; R, the receiver.

The diagram explains the general arrangement of the apparatus, mounted on an optical bench. The spark gap of the radiator is horizontal. The polariser, with the leaves vertical, is placed on a shelf attached to a screen of thick brass plate 35×35 cm. In the centre of the plate there is a circular opening 4 cm. in diameter; this aperture may be varied by a series of diaphragms. There is a second similar screen with a shelf for the analyser, which is placed with the leaves horizontal. Behind the analyser is the receiver.

In the space between the brass plates is placed the substance to be examined. Previous tests are made to see whether all disturbing causes have been removed. The sensitiveness of the receiver is occasionally tested by interposing one's finger at 45° between the crossed polariser and analyser; this should, by partially restoring the field, produce strong action, provided the receiver is in a fairly sensitive condition.

Care should be taken that there are no metallic masses between the screens, as reflection from metals is found to produce "depolarisation", the rays being then elliptically polarised. The substance to be examined should not, for very delicate experiments, be held by the hand, owing to the disturbing action of the fingers. It is preferable to have the substances supported on stirrups made of thin paper. The above are some of the main precautions to be taken in carrying out the following experiments, where the effects to be detected are very small and therefore likely to be masked unless all disturbing causes are carefully excluded.

I have in a previous communication made mention of the double refracting property of fibrous substances like jute. The field is restored when a bundle of jute is placed at 45° between the crossed polariser and analyser. There is, however, no depolarisation effect when the axis of the bundle is parallel to the direction of the ray.

I now took three similar bundles, A, B and C, of parallel fibres of jute 10 cm. in length and 4·5 cm. in diameter. No change was made in the bundle A which was kept as a test one. The bundles B and C were then twisted, B in a right-handed direction and C in a left-handed direction.

The interposition of the untwisted bundle A between the crossed polariser and analyser did not produce any effect, but strong action was produced in the receiver when the bundles, twisted to the right or to the left, were so interposed. It thus appeared as if the twisted structures produced an optical twist of the plane of polarisation.

Further experiments to be described below may be of some interest in connection with the optical rotation produced by liquids. Here two different classes of phenomena may be distinguished :—

(1) The rotation induced by magnetic field ; this rotation among other things is dependent on the direction and intensity of the magnetic field, and is doubled when the ray is reflected back.

(2) The rotation produced by saccharine and other solutions, when the rotation is equal in all directions and simply proportional to the quantity of active substance traversed by the ray ; the rotation in this case is neutralised when the ray is reflected back.

The difficulties in the way of explaining rotation produced by liquids are summarised in the following extract :—

" It is, perhaps, not surprising that crystalline substances should, on account of some special molecular arrangement, possess rotatory power, and affect the propagation of light within the mass in a manner depending on the direction of transmission. The loss of this power when the crystalline structure is destroyed, as when quartz is fused, is consequently an event which would be naturally expected, but the possession of it in all directions by fluids and solutions, in which there cannot be any special internal arrangement of the mass of the nature of a crystalline structure, is not a thing which one would have been led to expect beforehand. To Faraday it appeared to be a matter of no ordinary difficulty; it is just possible that the light, in traversing a solution in which the molecules are free to move, may, on account of some peculiarity of structure, cause the molecules to take up some special arrangement, so that the fluid becomes as it were polarised by the transmission of the light, in a manner somewhat analogous to that in which a fluid dielectric is polarised in a fluid of electrostatic force."*

In order to imitate the rotation produced by liquids like sugar solutions, I made small elements or "molecules" of twisted jute, of two varieties, one kind being twisted to the right (positive) and the other twisted to the left (negative). I now interposed a number of, say, the positive variety, end to end, between the crossed polariser and analyser; this produced a restoration of the field. The same was the case with the negative variety. *I now mixed equal numbers of the two varieties, and there was now no restoration of the field, the rotation produced by one variety being counteracted by the opposite rotation produced by the other.*

To get complete neutralisation, it is necessary that the element should be of the same size, and that the two varieties should be twisted (in opposite directions) to

* Preston, 'On Light,' 2nd ed., p. 421.

the same amount. The experiment was repeated in the following order, to avoid any uncertainty due to the possible variation of the sensitiveness of the receiver. The receiver is adjusted to a particular sensitiveness, and as long as it is not disturbed by the action of radiation, the sensitiveness remains constant. A mixture of opposite elements is first interposed, the receiver continuing to remain unaffected. From the mixture of positive and negative varieties, one set, say the negative, is now rapidly withdrawn, and an equal number of positive substituted. The receiver which has not been disturbed since its first adjustment is now found to respond, all the elements conspiring to produce rotation in the same direction. It will be seen that the two experiments are carried out under identical conditions.

In the above, we have electro-optic analogues of two varieties of sugar—dextrose and levulose. There is also the production of an apparently inactive variety by the mixture of two active ones.

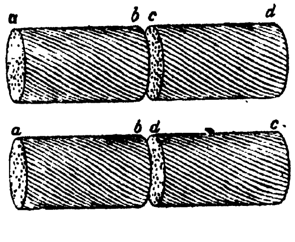


Fig. 20. Jute elements.

It is to be noted that there is no polarity in the elements, in the sense we use the term in reference to, say, magnetic molecules. *There is nothing to distinguish, one end of the jute element from the other end ; indeed a right-handed element would appear right-handed when* *looked at from either end.* It thus happens that if the rotation is determined by the direction of the twist, two molecules of the same variety will always conspire whether they are arranged as *ab*, *cd*, or, to take the extreme case, as *ab*, *dc* (with the second molecule reversed). The assumption of any particular arrangement of molecules is thus not necessary in explaining the rotation. The average effect produced by a large number of active elements interspersed in an inactive medium will thus be the same in all directions, and proportional to the number of molecules traversed by the ray. *As there is no polarity in the molecule*, a right-handed element will always produce the same kind of rotation, say, to the right of an observer travelling with the ray. The rotation produced when the ray is reversed by reflection will thus be in an opposite direction, and the two rotations will neutralise each other.

But if the molecules exhibit any polarity, that is to say, if the effects produced by the two ends of the same molecule are opposite, the resultant effect produced by a number of such molecules arranged in haphazard directions, will be zero. In order that the effects produced by the molecules may conspire, it is necessary that they should take up a special arrangement like the disposition of molecules in a magnetised rod. It is seen that in this case the rotations of the direct and the reflected rays are in the same direction, and the resultant rotation is therefore doubled. There is some analogy between the action of such polarised molecules and of substances which, when placed in a magnetic field, rotate the plane of polarisation.

(*Proc. Roy. Soc.*, *Mar.* 1898.)

XI

ON THE PRODUCTION OF A "DARK CROSS" IN THE FIELD OF ELECTRO-MAGNETIC RADIATION

A circular piece of chilled glass when interposed between crossed Nicols produces a dark cross. A similar effect is produced by crystals like salicine where there is a radial disposition of the principal planes.

I have been able to detect a similar phenomenon in the field of electric radiation by the interposition of an artificial structure between the crossed polariser and analyser.

I have in a previous communication described the polarisation produced by the leaves of a book. For the following experiment, a long strip of paper was rolled into a disc. A roll of Morse's tape serves the purpose very well. The diameter of the disc is 14 cm. and its thickness 2 cm. It will be observed that here we have a single axis passing through the centre, and that all planes passing through the centre are principal planes.

The effect produced by the interposition of the structure may be studied by keeping the disc fixed and exploring the different parts of the field by means of the detector; or the detector may be kept fixed (opposite the analyser) and the disc may be moved about so that the different parts of the field may successively be brought to act on the detector. This latter plan was adopted as being simpler in practice.

The arrangement of the apparatus is the same as in fig. 19 of my previous paper. The polariser is vertical and the analyser horizontal. The paper disc is interposed between the screens with its plane at right angles to the direction of the ray.

The receiver is fixed on the prolongation of the line (which I shall call the *axis*), joining the centres of the polariser and the analyser.

On the supposition that the interposition of the disc produces a dark cross, the arms of the cross (with the particular arrangement of the polariser and the analyser) will lie in the projections of the vertical and the horizontal diameters of the disc, and will move in space with the movements of the disc. When the centre of the disc is on the axis, the intersection of the cross will be superposed on the receiver, and there should then be no action. If the disc be moved up and down, the centre remaining in the vertical line passing through the axis, the vertical arm of the cross will slide over the receiver. If the disc be moved laterally, with its centre in the horizontal line passing through the axis, the horizontal arm of the cross will slide over the receiver. In this, as in the last case, there should be no action on the receiver. But if the disc be displaced so that the centre does not lie in either the horizontal or the vertical line passing through the axis (the axis now cutting the disc at points such as *a*, *b*, *c* or *d*), the arms of the cross will not fall on the receiver, and there should be a response in the receiver (see fig. 21).

The experiments were now arranged as follows :— The disc was at first placed with its centre on the axis, the plane of the disc being perpendicular to the axis. There was now no action on the receiver ; but as soon as the disc was tilted, however slightly, an action was immediately produced on the receiver.

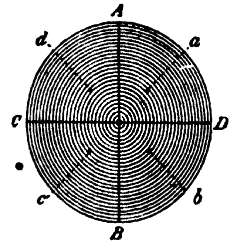


Fig. 21. The paper disc. AB, CD are the vertical and horizontal diameters.

The disc was now mounted on a stand, between the two screens. By means of sliding arrangements the disc could be raised or lowered, or moved laterally.

In the next experiment, the centre of the disc was first adjusted on the axis, and the disc moved vertically up and down. No effect was produced when this was being done.

The centre of the axis was again adjusted on the axis, and the disc moved laterally on the horizontal slide. In this case, too, there was no action.

By adjusting the vertical sliding rod the centre of

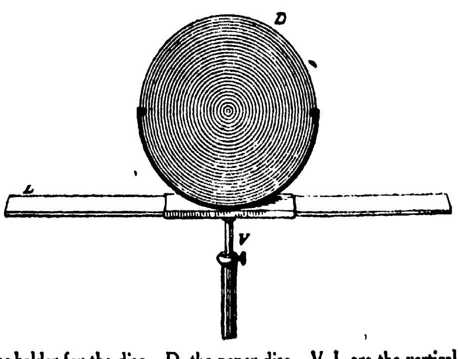


Fig. 22. The holder for the disc. D, the paper disc. V, L are the vertical and horizontal slides.

the disc was next placed vertically above or below the axis. The disc was then moved laterally either to the right or to the left. In this way the field could be displaced, and the quadrants *a*, *b*, *c*, or *d* (*cf*. fig. 21) placed opposite to the receiver. In all these cases, even with small displacements, very strong action was produced on the receiver.

From experiments carried out in the manner described above, the outline of a dark cross projected in space was distinctly made out.

The production of a dark cross can also be demonstrated by interposing between the crossed polariser and analyser concentric rings of tin-foil mounted on a thin sheet of mica. But greater interest is attached to the exhibition of the phenomenon by double refracting substances, where the axes of elasticity are disposed in radial directions. From the peculiar stresses present, I surmised that woody stems with concentric rings would exhibit the phenomenon above described. I experimented with transverse sections of stems of *Pinus longifolia*, *Swietenia mahogani*, *Araucaria Cunninghamii*, *Mangifera indica*, *Casuarina equisetifolia*, *Cupressus torulosa* and *Dalbergia sissoo*. The ring systems present in some of these were very regular. I was, however, at first disappointed in failing to obtain the results anticipated. But this failure, I subsequently found, was due to the general opacity of the wood which was freshly cut, and which, though apparently dry, contained large quantities of sap in the interior. I then carefully dried some of the specimens, when the stresses present became quite apparent by numerous cracks starting in radial directions. The results obtained with these dried specimens were quite satisfactory.

I now tried to devise some experiments strictly analogous to the optical experiments with chilled glass. I obtained extremely good results with a cylinder of cast ebonite, in which the stresses present are exactly similar to those in a circular piece of unannealed glass.

The next series of experiments were undertaken with mineral specimens. One very interesting object obtained from Egypt was formed by ringed concretion of flint round a central nodule. This specimen exhibited the cross with great distinctness. I also obtained fairly satisfactory results with stalactite. The concretion of calcium carbonate formed inside a pipe by deposits from temporarily hard water flowing through it, would also be found to exhibit this phenomenon.

(*Proc. Roy. Soc., March* 1898.)

XII

ON A SELF-RECOVERING COHERER AND THE STUDY OF THE COHERING ACTION OF DIFFERENT METALS

In working with coherers, made of iron or steel, some special difficulties are encountered in the warm and damp climate of Bengal. The surface of the metals soon gets oxidised, and this is attended with variation of sensitiveness of coherer. The sensitiveness, it is true, does not altogether disappear, but it undergoes a considerable diminution. The presence of excessive moisture in the atmosphere introduces another difficulty. Substances to be experimented on become more or less opaque by absorption of water vapour. As fairly dry weather lasts in Bengal only for a few weeks in winter, the difficulties alluded to above are for the greater part of the year serious drawbacks in carrying out delicate experiments. To avoid as far as possible the partial loss of sensibility of the receiver due to oxidation, I tried to use metals less oxidisable than iron for the construction of the coherer. In my earlier experiments I derived considerable advantage by coating the steel spirals with deposits of various metals. Finding that the sensitiveness depends on the coating metal and not on the substratum, I used in my later experiments fine silver threads wound in narrow spirals. They were then coated with cobalt in an electrolytic bath. The coating of cobalt was at first apt to strip off, but with a suitable modification of the electrolyte and a proper adjustment of the current, a deposit was obtained which was very coherent. The contact surface of cobalt was found to be highly sensitive to electric radiation, and the surface is not liable to such chemical changes as are experienced in the case of steel.

I next proceeded to make a systematic study of the action of different metals as regards their cohering properties. In a previous paper I enumerated the conditions which are favourable for making the coherer sensitive to electric radiation. These are the proper adjustment of the E. M. F. and pressure of contact suitable for each particular receiver. The E. M. F. is adjusted by a potentiometer slide. For very delicate adjustments of pressure I used in some of the following experiments an U-tube filled with mercury, with a plunger in one of the limbs; various substances were adjusted to touch barely the mercury in the other limb. A thin rod, acting as a plunger, was made to dip to a more or less extent in the mercury by a slide arrangement. In this way the mercury displaced was made to make contact with the given metal with gradually increasing pressure, this increase of pressure being capable of the finest adjustment. The circuit was completed through the metal and mercury. Sometimes the variation of pressure was produced by a pressure bulb. In the arrangement described above the contact is between different metals and mercury; metals which were even amalgamated by mercury still exhibited sensitiveness to electric radiation when the amalgamation did not proceed too far. In this way I was able to detect the cohering action of many conductors, including carbon. For studying the contact-sensitiveness of similar metals I made an iron-float on which was soldered a split tube in which the given metal could be fixed, a similar piece of metal being adjusted above the float, so that by working the plunger or the pressure bulb the two metals could be brought into contact with graduated pressure. The other arrangements adopted were the contact of spirals compressed by micrometer screw, and filings similarly compressed between two electrodes.

With the arrangement described above the action of radiation on metallic contacts was studied, a brief account of which will be given under their respective groupings. It may here be mentioned that certain metals which do not usually show any contact-sensitiveness can be made to exhibit it by very careful manipulation. The nature of the response of a coherer is to a certain extent modified by its condition and particular adjustment. A coherer freshly made is more difficult to adjust, but at the same time far more sensitive. The action is more easily under control and more consistent after a few days' rest, but the sensitiveness is not so abnormally great. The contacts of clean surfaces are difficult to adjust, but such contacts are more sensitive than those made by surfaces which are tarnished. Pressure and E. M. F., as previously stated, also modify the reaction. For example, a freshly made and very delicately adjusted coherer subjected to slight pressure and small E. M. F. showed an *increase* of resistance by the action of radiation. The galvanometer spot after a short interval, resumed its former position, exhibiting a recovery from the effect of radiation. The coherer continued to exhibit this effect for some time, then it relapsed into the more stable condition in which a diminution of resistance is produced by the action of radiation. Another coherer was found apparently irresponsive to radiation, there being the merest throb (sometimes even this was wanting) in the galvanometer spot, when a flash of radiation fell on the receiver. Thinking that this apparent immobility of the galvanometer spot may be due to response, followed by instantaneous recovery, the galvanometer needle being subjected to opposite impulses in rapid succession, I interposed a telephone in the circuit; each time a flash of radiation fell on the receiver the telephone sounded, no tapping being necessary to restore the sensitiveness. The recovery was here automatic and rapid. After twenty or thirty flashes, however, the receiver lost its power of automatic recovery, and the sensitiveness had then to be restored by tapping. An interesting observation was made to the effect that on the last occasion the receiver responded without previous tapping, a rumbling noise was heard in the telephone which lasted for a short time, evidently due to the rearrangement of the surface molecules to a more stable condition, after which the power of self-recovery was lost.

The state of sensibility described above is more or less transitory, and is induced, generally speaking, by a somewhat unstable contact and low E. M. F. acting in the circuit. In the majority of metals, the normal tendency is towards a diminution of contact resistance by the action of electric waves. The occasional increase of resistance, in general, disappears when the pressure and E. M. F. are increased. But in the case to be presently described there is an interesting exception, where the normal state of things is just the reverse of what prevails in the majority of metals.

Alkali Metals

In the following investigations the radiator is a platinum sphere 9·7 mm. in diameter. The coherer was placed at a short distance, so that the intensity of incident radiation was fairly strong.

Potassium.—In working with this metal, the exceptional nature of the reaction became at once evident. The effect of radiation was to produce an *increase* of resistance. The pressure of contact was adjusted till a current flowed through the galvanometer, the galvanometer spot of light being at one end of the scale. On subjecting the receiver to radiation the spot of light was deflected to the opposite end, exhibiting a great increase of resistance. When the pressure and E. M. F. were suitably adjusted a condition was soon attained, when a flash of radiation made the spot of light swing energetically in one direction, indicating an increase of resistance: the receiver recovered instantaneously on the cessation of radiation, and the spot violently swung back to the opposite end, indicating the normal current that flows in the circuit. This condition was found to persist, the receiver uniformly responding with an increase of resistance followed by automatic and instantaneous recovery. To prevent oxidation, the receiver was kept immersed in kerosene. When the receiver was lifted from the protecting bath, it still continued to respond with an increase of resistance, but with a gradual loss of power of automatic recovery. This power was again restored on re-immersion of the coherer in kerosene. The receiver in vacuo, or under reduced hydrogen pressure, would have been preferred, had the necessary appliances been available.

Sodium.—As we pass from potassium to the neighbouring metals, there is a gradual transition of property as regards the nature of response to electric waves. With sodium the adjustment is a little more difficult than with potassium, but the response is somewhat similar to that of potassium. Though, in general, there is an increase of resistance produced by electric radiation, there are occasional exceptions when a diminution of resistance is produced. With some trouble the adjustment could be made so that the recovery is also automatic, but it is not so energetic as in the case of potassium.

Lithium.—Specimens of this metal not being available, I obtained a deposit of it on iron electrodes by electrolysis of the fused chloride. The action produced by electric radiation was sometimes an increase and sometimes a diminution of resistance, the increase of resistance being the more frequent. With some difficulty it was possible to adjust the sensitiveness so that the recovery was automatic, but it was not energetic nor did this power persist for a long time.

Metals of the Alkaline Earth

Pure metals of this group being not available, I had to rely on the deposit obtained by electrolysis. Chloride of calcium was fused in a crucible, and deposits were produced on iron cathodes, the anode being a carbon rod. The deposit was not very even. One of the iron rods with the deposit was tested by immersion under water, when hydrogen was evolved. I did not succeed in getting deposits of either barium or strontium, the temperature available not being sufficiently high.

On making a coherer with calcium, and keeping it immersed in kerosene, an action similar to that produced by sodium was observed. The tendency of self-recovery was, however, very slight.

Magnesium, Zinc, and Cadmium

In these metals and in the succeeding groups there is a pronounced tendency towards a diminution of resistance by the action of electric radiation. Magnesium being easily oxidisable, there is a thin coating of oxide on the surface. When this is scraped, the metal makes a very highly sensitive receiver. The adjustment is not difficult, the metal allowing a considerable latitude of pressure and E. M. F. It has already been stated that the metals which are slightly tarnished can be more easily adjusted.

Though there is in this metal a decided tendency towards a reduction of contact resistance, yet it is possible by careful adjustment to obtain an increase of resistance. Indeed it is sometimes possible to so adjust matters that one flash of radiation produces a diminution of resistance, and the very next flash an increase of resistance. Thus a series of flashes may be made to produce alternate throws of the galvanometer needle. The more stable adjustment, however, gives a diminution of resistance, and receivers made with this metal could be made extremely sensitive. The tendency towards automatic recovery is almost wanting.

Zinc.—This metal also exhibits moderate sensitiveness; it, however, requires a more careful adjustment.

Cadmium.—The action of this metal is somewhat similar to that of zinc, but the sensitiveness is very much less.

Bismuth and Antimony

Both bismuth and antimony make very sensitive receivers. Moderately small E. M. F. with slight pressure is best suited for these metals.

Iron and the Allied Metals

Iron.—The action of this metal is well known. In one of my experiments I used it in connection with mercury. When the contact is very lightly made, there is a tendency towards an increase of resistance by the action of radiation. But after a time the action becomes normal, that is to say, there is a diminution of resistance.

Nickel and Cobalt.—These are also very sensitive. The surface being bright, the E. M. F. and pressure are to be adjusted with some care.

Manganese and Chromium.—These were obtained in the form of powder. Their action is similar to the other metals of this group.

Aluminium.—This also makes a very sensitive receiver.

Tin, Lead and Thallium

It is somewhat difficult to adjust *tin*, but when this is done the metal exhibits fair sensitiveness. *Lead* is also sensitive. The sensitiveness of *thallium* is only moderate.

Molybdenum and Uranium

The specimen obtained was in the form of powder, and very tarnished in appearance. The sensitiveness exhibited was slight.

Metals of the Platinum Group

Platinum exhibited a moderate amount of sensitiveness. Spongy platinum also showed the same action. The absorption of hydrogen made the action slightly better, but the improvement was not very marked.

Palladium.—This made a more sensitive coherer than platinum. The adjustment is, however, more troublesome.

Osmium.—The specimen was in the form of powder. It required a higher E. M. F. to bring it to a sensitive condition. The sensitiveness was moderate.

Rhodium was found to be more sensitive than osmium.

Copper, Gold and Silver

Copper required a much smaller E. M. F. The sensitiveness was only moderate.

Gold was more difficult to adjust, but the action was a little stronger.

Silver.—The receiver was extremely unstable. It exhibited sometimes a diminution and at other times an increase of resistance.

It will be seen from the above that all metals exhibit contact-sensitiveness to electric radiation, the general tendency being towards a diminution of resistance.

The most interesting and typically exceptional case, however, is the receiver made with potassium, which not only exhibits an increase of resistance by the action of radiation, but also a remarkable power of self-recovery. In the instances of increase of resistance exhibited by other metals, an increase of pressure or E. M. F. generally brought the coherer to the normal condition, which showed a diminution of contact resistance by the action of electric waves. With potassium

I gradually increased the pressure till the receiver grew insensitive. All along it indicated an increase of resistance, even when one piece was partially flattened against the other. I increased the E. M. F. many times the normal value ; this increase (till the limit of sensitiveness was reached) rather augmented the sensibility and power of automatic recovery. I allowed the receiver a period of rest, the nature of response remaining the same. As far as I have tried, potassium receivers always gave an increase of resistance, a property which seems to be characteristic of this metal, and to a less extent, of the allied metals.

It will thus be seen that the action of potassium receiver cannot be regarded as a cohering one. For it is difficult to see how a cohering action and consequent better contact could produce an increase of resistance.

In arranging the metals according to their property of change of contact resistance, I was struck by the similarity of action of electric radiation on potassium in increasing the contact resistance, and the checking action of visible radiation on the spark discharge. In the latter case also, potassium is photo-electrically the most sensitive. But the action is confined to visible radiation, and is most efficient in the ultra-violet region. I was indeed apprehensive that the action on potassium receiver which I observed might be in some way due to the ultra-violet radiation of the oscillatory spark. But this misgiving was put to rest from the consideration that the receiver was placed in a glass vessel filled with kerosene, through which no ultra-violet light could have been transmitted. For putting the matter to final test, I lighted a magnesium wire in close proximity to the receiver without producing any effect. Thick blocks of wood, of ebonite and of pitch were interposed without checking the action. I then used polarised electric radiation, and interposed a book analyser, 6 cm. in thickness; when the analyser was held parallel, there was a vigorous action, but when it was held in a crossed position all action was stopped. No visible or heat radiation could have been transmitted through such a structure, and there can be no doubt that the action was entirely due to electric radiation.

(*Proc. Roy. Soc.*, *Apr.* 1899.)

XIII

ON ELECTRIC *TOUCH* AND THE MOLECULAR CHANGES INDUCED IN MATTER BY ELECTRIC WAVES

In the various investigations on the properties of electric waves, one property has not yet attracted so much attention as it deserves—the action of long ether waves in modifying the molecular structure of matter. Apart from the interest attached to the relation between ether, electricity, and matter, the subject is of importance as affording not only a very important verification of the identity of visible and electric radiation, but also establishing the continuity of all radiation phenomena. These occupy the borderland between physics and chemistry, and their study may therefore be expected to throw much light on several subjects at present imperfectly understood. The study of the action of electricity and of ether waves on matter in the form of solids presents many difficulties, owing to the great complexity of atomic and molecular aggregation which characterises the solid state of matter. But the phenomena often met with in theory and practice are, unfortunately, in reference to matter in the solid state. The means of investigation are almost wanting: chemical tests give us no information, for they tell us (and that in a few cases only) of the ultimate change in the mass as a whole, and not of the protean transformations that are constantly taking place in it, under the action of ever-varying changes in physical environments. In the following investigations the difficulties mentioned above were constantly present, and the attempts to meet them may therefore be of some interest.

I have already described the contact-sensitiveness of various elementary substances to electric radiation. It was shown that though many substances exhibit a diminution of contact-resistance, there are others which show an increase of resistance which, in certain cases, lasts only during the impact of electric waves, the sensitive substance automatically recovering its original conductivity on the cessation of radiation. There are thus produced two opposite effects, either an increase or a diminution of resistance, depending on the nature of the substance.

The effect of increase of contact-resistance is not an exceptional or isolated phenomenon, but is as normal and definite under varied conditions as the diminution of resistance noticed in the case of iron filings. These two specifically different effects have to be recognised, and it would be advisable, to avoid misunderstanding, to use a simple term to indicate both these effects, and distinguish them from one another, by calling the one positive and the other negative. The term " coherence" applied to the normal *diminution* of resistance exhibited by certain metals by the action of electric waves cannot be applied in all cases; for, as has been said before, there is another class of substances which exhibits under *normal* conditions an *increase* of resistance. The term " decoherence " has been used to indicate the effect of mechanical tapping, on fatigued substances of the former class; this produces an increase of resistance, and at the same time restores the sensitiveness. The action of tapping on fatigued specimens of the latter class is, however, a diminution of resistance.

I have shown in a former paper that the seat of sensitiveness is confined mainly to the surface layer of the sensitive substance, and that the nature of the substratum has little or no effect on the sensitiveness. Thus, a substance which exhibits a strong diminution of resistance, if coated with an extremely thin layer of a substance of the other class which shows an increase of resistance, will now exhibit an increase of resistance. It is seen that the re-action is one of the bounding layer or skin of the sensitive substance. There is a Sanskrit word, *twach*, which means the skin; and as the phenomenon dealt with in the present paper is one of sensitiveness of *twach*, I shall use the expression "electric *touch*" in the restricted sense of contact sensitiveness to electric stimulus, the touch being regarded as *positive* when electric oscillation produces an increase of conductivity or diminution of resistance, and *negative* when the contrary effect is produced. Substances which exhibit a decrease of resistance will be called positive, and those which show an increase will be regarded as negative. The above terms are to be regarded as convenient substitutes for long descriptive phrases.

The phenomenon of contact-sensitiveness seems at first to be extremely anomalous, and there appears to be little relation between substances which exhibit similar electric sensitiveness. Taking iron as an example of a very sensitive substance, it is seen to be easily oxidised, and from this it may be inferred that a slight oxidation on the surface is favourable for sensitiveness. This view obtains some support from the consideration that the so-called noble metals are not as sensitive as iron. But the metals nickel and cobalt, which are bright and not easily oxidised, are also highly sensitive. The very sensitive metals iron, nickel, and cobalt are all magnetic, and it might be thought that magnetic property is favourable for electric sensitiveness, but a diamagnetic substance like bismuth is also found to exhibit a fairly strong sensitiveness. Again, from the strong diminution of resistance exhibited by magnesium, it may be inferred that the sensitiveness depends on the electro-positive character of the metal; but potassium, one of the most electro-positive metals, exhibits the unusual increase of resistance.

There is one property, however, which at first would seem to be in some way related to the sensitiveness of metals—the volatility of metals under the cathodic stimulus, investigated by Sir William Crookes,* who gives the following list of metals, arranged according to their volatility:—

Palladium	108	Copper	40
Gold	100	Cadmium	31·99
Silver	80·68	Nickel	10·99
Lead	75·04	Indium	10·49
Tin	56·96	Iron	5·5
Brass	51·58	Magnesium	very slight
Platinum	44	Aluminium	very slight

In this list the substances which are most volatile, *e.g.*, Pd, Au, Ag, are not very sensitive, whereas Fe, Al, Mg, which are least volatile, are strongly sensitive. But the above series does not exactly coincide with the series of electric sensitiveness. Again, the volatility of platinum is retarded in hydrogen gas, but an experiment carried out to determine the sensitiveness of plati-

* Crookes, 'Roy. Soc. Proc.', vol. 50.

num in hydrogen failed to show any great increase in the sensitiveness.

None of the above suppositions give any satisfactory explanation of the numerous anomalies in the contact-sensitiveness of metals. It then appeared that the observed effect is not due to a single cause but to many causes. An observer studying the dilatation of a gas under reduced pressure, and ignorant of the effect of temperature, will doubtless encounter many anomalies. In the phenomena of contact-sensitiveness the variables are, however, far more numerous, and the different possible combinations are practically unlimited. It therefore became necessary, by a long and tedious process of successive elimination, to find out the causes which are instrumental in producing the observed effect; the results obtained throw some light on this intricate subject. The following are some of the principal directions in which a systematic inquiry was carried out:

A. On the difference between mass action and molecular or atomic action, with reference to the phenomenon of contact-sensitiveness.

B. On the change of sign of response in a receiver due to a variation of radiation intensity.

C. On the physico-chemical changes produced in a sensitive substance by the action of electric radiation, and on the radiation-product.

D. The phenomena of electric reversal and of radio-molecular oscillation.

E. On "fatigue" and the action of mechanical tapping and other disturbances by which the sensitiveness of a fatigued receiver may be restored.

F. On the relation between variation of electromotive force and resulting current through imperfect contacts.

G. On the systematic study of the contact-sensitiveness exhibited by metals, non-metals and metalloids.

H. On the contact-sensitiveness exhibited by alloys and compounds.

I intend to treat the above subjects in some detail, and in the present paper will especially deal with the first five lines of investigation. These, it is hoped, will afford an explanation of some of the most perplexing anomalies. All the subjects mentioned above are more or less interdependent, but their treatment in one paper would make the subject very complicated. It would be easier to take a more generalised and complete view of the subject as a whole, after each of the above-mentioned inquiries has been separately considered. With reference to the flow of electricity through imperfect contacts, I need only mention here that the phenomenon seldom obeys Ohm's law. There are in fact two characteristically different types, in the first of which the current is disproportionally increased under increased electromotive force; in the second we are presented with the astonishing result that the current is actually diminished under increasing electromotive force.

Mass Action and Molecular Action

Of the various attempts made to explain the action of contact-sensitiveness, Professor Lodge's theory of coherence has been the most suggestive. The coalescence of water and mercury drops in Lord Rayleigh's experiments, and Professor Lodge's observation of the welding of two metallic spheres by powerful oscillatory discharge in the neighbourhood, apparently lend much support to the theory of electric welding, which explains in a simple manner the diminution of contact-resistance of various metallic filings when subjected to strong electric variation.

On this theory it follows that *all* imperfect contacts should exhibit a diminution of resistance when subjected to electric radiation. In carrrying out a systematic investigation of the contact-sensitiveness of metals, I, however, found that there are substances, of which potassium may be taken as a type, which exhibit an increase of resistance. Potassium is not a solitary instance; I have found a large number of elements exhibiting this action; the number of compounds which exhibits a similar action is also considerable. Other experiments will be presently described which would show that the theory of coherence is inadequate. From the above it would appear that the subject is far more complex than was at first supposed. For various reasons it would be best to distinguish between two different classes of reaction, which may conveniently be described as mass action and molecular action.

Mass Action.—By this it is meant the general action, say, between two masses when placed in a very strong electric field. Under the given circumstance, sparking may take place between the bodies, and the two may thus be welded together. From what has been said it will be seen that such action is *non-discriminative*—that is to say, the action will be the same whatever the chemical or physical nature of the substance may be. The best way of showing this action is with drops of liquid, with surface contamination, for any incipient welding will be at once exhibited by the complete coalescence of the drops. The non-discriminative nature of the action is shown in a striking manner in the following experiment. I may mention here that fragments of solid potassium, and in a lesser degree sodium, exhibit an increase of contact-resistance under the action of electric waves. I made a liquid alloy of potassium and sodium, and drops of this alloy were allowed to float on the stratum separating dense Rangoon oil from lighter kerosene, the alloy being of an intermediate density. The drops coalesced when placed in an intense alternating electric field. The next experiment was made with potassium heated under melted (hard) paraffin. By stirring the molten K with a glass rod, the metal was broken up into numerous spherical drops. These also coalesced under similar electric influence. It is, however, to be borne in mind (1) that in the above experiment the substance is in the form of a liquid, and that in this particular condition certain important molecular changes, to be presently described, cannot very well take place; (2) that the conditions of the experiment are abnormal.

Experiments will be presently described which will show that the observed variation of conductivity produced by radiation is not due to coherence, but to certain molecular changes of an allotropic nature.

Molecular Action.—By this is meant the allotropic modification produced in a substance by the action of electric waves, the allotropic change being due to a difference in the atomic or molecular aggregation. It will be shown that such molecular change does take place by the action of electric waves, and that all the observed effects of variation of resistance of the sensitive substance may be explained on the theory of allotropic transformation due to the above cause. The effect due to molecular changes in a substance is also expected to be modified by the chemical nature of the substance; thus the molecular action due to radiation, giving rise ultimately to the variation of conductivity of the sensitive substance, will be *discriminative* in contradistinction to the non-discriminative mass action.

Is the effect of radiation due to non-discriminative coherer action or to the discriminative molecular action? That the effect is discriminative, and therefore molecular, appears to be decisively proved by the experiments described below. If further proofs are necessary they are afforded by the characteristic curves of variation of current with the E. M. F. given by the three types of substances, positive, negative, and neutral; by the continuity of radiation effect on matter; and, lastly, by certain remarkable results I obtained, which show that the effect of ether waves on elementary substances depends on the chemical nature of the substance; in other words, the effect is found to be a periodic function of the atomic weight of the substance. Detailed accounts of the above are for the present deferred for a future occasion.

On the Change of Sign of Response in the Receiver, due to a Variation of Intensity of Radiation

After finding the increase of resistance exhibited by certain substances, I wished to see whether these showed any further difference as compared to substances which exhibit a diminution of resistance. In my determination of the "Index of Refraction of Sulphur for the Electric Ray," I used the method of total reflection. I often noticed that just before total reflection, when the intensity of the transmitted beam became comparatively feeble, the receiver indicated an increase instead of the normal diminution of resistance. Professor Lodge mentions in one of his papers that an iron filing coherer exhibits an increase of resistance when acted on by feeble radiation. If the normal sign of response is reversed by a feeble intensity of stimulus, then negative substances may be expected to give a positive reaction with feeble radiation. Very sensitive substances are, however, not so well adapted for an exhibition of this reversed action possibly because the range of sensibility is comparatively great. But it is not difficult to demonstrate this property in the case of moderately sensitive substances.

The following experiment with a moderately negative substance (arsenic) and a moderately positive substance (osmium) will bring out this interesting peculiarity in a clear manner. The intensity of incident radiation may be varied in two ways; (1) by removing the radiator further and further from the receiver, or (2) by using polarised radiation, whose intensity may be varied by the rotation of an analyser. In the experiment to be described, the first method was adopted.

Experiments with Arsenic Receiver.—A receiver was made of freshly-powdered arsenic. The radiator used emitted radiation of strong intensity. It was at first placed close to the receiver, and there was produced a moderate increase of resistance. It was then removed further and further, and the increase of resistance became less and less. When the distance was increased to 25 cm. the action was reduced to zero; when this was further increased to 30 cm. there was a diminution of resistance, showing that 25 cm. is, in this case, the *critical* distance. The receiver continued to exhibit a diminution until the radiator was removed to a distance of 70 cm., when the radiation intensity was too feeble to affect the receiver. Now this critical distance may approximately be regarded as a measure of the sensibility of the substance. In this particular case the electric touch has a negative sign. If by any means (some of which will be described later on) the substance becomes more sensitive, *i.e.*, more negative, the critical distance will be increased. On the contrary, if the sensitiveness becomes less (the substance tending towards positive direction) the critical distance will be decreased. The application of this principle is of importance as affording a means of determining the variation of sensitiveness under different conditions.

Experiments with Osmium Receiver.—Substances which are feebly positive give a diminution of resistance when the radiator is close to the receiver, and an increase of resistance when the radiator is beyond the critical distance. Thus the critical distance for an osmium receiver (whose normal action is moderately positive) was found to be about 250 cm. At the reduced distance of 50 cm. the response was +150 divisions; this was diminished to +4 when the distance was increased to 200 cm. But at a distance of 300 cm. when the intensity of radiation was so feeble as to be below the critical, the response was reversed to —3 divisions.

In order to avoid confusion, we may choose to call the effect due to strong intensity of radiation as the normal action. The sign of normal action might further be verified, wherever possible, by obtaining a reverse action under feeble intensity of radiation.

Molecular Changes produced in Matter by the Action of Electric Waves

A sensitive receiver made, say, of iron powder, has its conductivity suddenly increased by the action of electric radiation; but the sensitiveness of the receiver is lost after the first response, and it is necessary to tap it to restore the sensitiveness. On the theory of coherence, the loss of sensitiveness is explained by supposing that electric radiation brings the particles nearer and welds them together, and that the sensitiveness can then only be restored by the mechanical separation of the particles. This supposition, however, fails in the case of substances which exhibit an increase of resistance by the action of radiation. It may, however, be supposed that by some process, little understood, the particles are slightly separated by the action of electric waves, thus producing the observed increase of resistance. On this view, however, the restoration of sensitiveness by tapping remains unexplained. Again, if the increase of resistance is due to a slight separation of particles, suitable small increase of pressure ought to restore the original conductivity, as also the sensitiveness. It is, however, found that a considerable pressure is required to restore the original current, as if the outer layers of the particles were rendered partially non-conducting by radiation, and had to be broken through before the original current could be re-established. It is also found that though the sensitiveness is restored by this expedient of increasing the pressure, yet the restoration is only partial, and that after a repetition of this process the receiver loses its sensitiveness almost completely.

I have attempted to find out an explanation of this obscure "fatigue" effect. This subject will best be treated in connection with the anomalous behaviour of silver, which I find is also in a manner connected with the fatigue effect. Silver, when subjected to radiation, exhibits, as indicated in my last paper, sometimes an increase, and at other times a decrease, of resistance. The difficulty in this case cannot be explained on the supposition of variations of radiation intensity, as the anomaly persists even when the intensity of radiation is maintained uniform by keeping the radiator at a fixed distance.

In order to explain these actions, I assumed the following hypotheses, which, with the necessary deductions, are given below :—

(1) That electric radiation produces molecular change or allotropic modification in a substance.

(2) That, starting from the original molecular condition A, the effect of radiation is to convert it, to a more or less extent, into the allotropic modification B (the latter condition will be designated as the "radiation product"). It follows that this change from one state to the other must be accompanied by a corresponding change in the physical properties of the substance.

(3) As one of the properties of a substance is its electric conductivity, any allotropic change

produced by radiation should be capable of being detected by a variation in the conductivity of the substance.

(4) As a molecular strain is produced during transformation from A to B, at a certain stage there may be a rebound towards the original state A. Thus, after the molecular change from A to B condition has reached a maximum value, the further action of radiation may be to reconvert, to a more or less extent, B to A, this reversal of effect being indicated (see No. 3) by a corresponding electric reversal.

(5) That the ultimate loss of sensitiveness, known as "fatigue", is due to the presence of the radiation product, or strained B variety, along with the A variety, the opposite effects produced by the two varieties neutralising each other.

The justification for the above hypotheses is to be sought for—

(1) From analogy with other known radiation phenomena.

(2) From experimental proof:

(*a*) Of the allotropic transformation being attended with changes in the conductivity of the substance.

(*b*) Of the existence (and, if possible, the production by chemical means) of an allotropic modification analogous to the radiation product or B variety, whose reaction should be opposite to that of the substance in a normal condition (A variety).

(*c*) Of the assumption that after the maximum transformation of A into B, the further action of radiation is to reconvert, to a more or less extent, the form B into A, such transformations giving rise to electric reversals.

(*d*) Of the existence of the radiation product in a fatigued specimen.

The above mentioned hypotheses will obtain still stronger support if further deductions from the above theory are borne out by confirmatory experiments.

I will now describe investigations on the lines sketched above.

Allotropic Modification produced by Visible Radiation

As regards the action of radiation in producing allotropic modification, several such instances are known in the case of visible radiation. In the familiar example, of the conversion of yellow phosphorus into the red variety, the effect is quite apparent. But this is not the case in the transformation of the soluble sulphur into an insoluble variety by the action of light ; here the transformation is not apparent, and has to be indirectly inferred from the insolubility of the solarised product in carbon bisulphide. The reason why a far larger number of instances of allotropic transformation produced by light is unknown, is not because such effects are not more numerous, but because we are unable to detect such minute changes. It must be admitted that our knowledge of molecular changes, specially in a solid, and the means of their detection, is at present extremely limited.

Variation of Conductivity produced by Allotropic Changes

There is one method of detecting these molecular variations to which little attention has hitherto been given, but which appears to be of great interest, and promises to yield important results in investigations of this class. It is evident that changes in molecular structure must be attended with changes of physical properties, electric conductivity being one of them. Among other instances of allotropic changes attended with changes in electric conductivity may be mentioned the wide difference of conducting power between graphite and diamond. The same great differences of conductivity is seen between the crystalline and amorphous varieties of silicon, and between the "metallic" and normal varieties of phosphorus. But it is not at all necessary to take only such extreme cases to show the influence of molecular or atomic aggregation in influencing the conductivity. This effect is brought into painful prominence by the variation produced, in spite of all precautions, in our standards of resistance.

Experimental Proof of Allotropic Changes being attended with variation of Conductivity.—I shall now describe a direct experiment by which the change of conductivity produced in a substance by molecular change is exhibited. Red mercuric iodide is converted into the yellow variety by the application of heat, and the substance does not return to its original state till after a considerable lapse of time. The recovery here is very slow. A small quantity of mercuric iodide was now placed in a tube provided with sliding electrodes, and a current was made to pass through the substance by suitable compression. The conductivity of the substance is rather small, and therefore a thin stratum should be taken for experiment. The current is observed by means of a sensitive galvanometer. On the application of heat to the tube (which converts the red into the yellow variety), there was at once produced, simultaneously with the molecular transformation, an increase of conductivity. This effect is not due to a rise of temperature, for the increased conductivity was still exhibited on cooling the tube. From this experiment it is seen that the molecular changes can be inferred from changes in the conductivity. In the case described above, the recovery from the B, or second stage, to the first stage, A, is slow; but there may be substances (and there are such substances) where, under the given conditions of temperature and other physical surroundings, the first stage is far more stable than the second; the substance will then pass back quickly from the B condition to the primitive state, on the cessation of the exciting cause which gave rise to the transient B effect. The substance will in this case be "self-recovering."

Electrical Reversal in the Radiation Product

In the hypotheses given above, it was said that the reaction of the radiation product, or B variety, should be opposite to that of the substance in the normal condition, or in the A state. Thus a negative substance which by the action of radiation shows an increase of resistance during conversion from the A to the B state should exhibit a diminution of resistance when B variety is acted on by electric waves. The contrary would be the case with positive substances.

The following tabulated statement indicates the phenomena exhibited by two classes of substances :—

Sign of electric touch.	Action of radiation on the fresh or A variety of the substance.	Further action of radiation on the radiation product or B variety.
Positive, *e.g.*, iron .	Diminution of resistance.	Increase of resistance.
Negative, *e.g.*, arsenic	Increase of resistance	Diminution of resistance.

We have thus two distinct classes of phenomena dependent on the sign of electric touch. If K_A represents the conductivity of the fresh substance, and K_B the conductivity of the radiation product, then—

(1) With positive substances, as the conductivity of the radiation product is greater ($K_B > K_A$), the first action of radiation would be to produce a diminution of resistance. This diminution will continue to be exhibited till the maximum amount of B variety is produced. The further action of radiation now will be to reconvert B into A; but as $K_A < K_B$ there would now be produced a diminution of conductivity, and a galvanometer in circuit will indicate an electrical reversal. The reconverted A variety may again be transformed to a greater or less extent to B, and in this way a series of reversals may take place, due to the continued action of radiation producing oscillation in

molecular or atomic groupings. I shall designate this as the phenomenon of radio-molecular oscillation.

(2) With negative substances the conductivity of the radiation product is less ($K_B < K_A$), and the first action of radiation will therefore be an increase of resistance. The phenomena exhibited by these negative substances will precisely be opposite to those shown by the positive substances.

The above is but an approximate representation of the phenomena. To be more accurate, one has to take into account the partial changes and the effect of radiation on these changed products. Thus, at first suppose the substance to be entirely made up of A variety (this would rarely be the case). The first flash of radiation converts a large portion of A into B, the substance now being a mixture of A and B. The action of the next flash would be to convert the unchanged A into B, and reconvert to a more or less extent B into A. The electric response will thus be very strong at the beginning, but will become continuously less and less. When the proportion of B has attained a maximum value, the reconversion of B into A will become relatively large, and thus give rise to reversal effect.

I spoke of the conversion "to a greater or less extent" of one variety into the other. There is also the question of the relative stability of the two varieties under the given conditions. From the above it will be seen what possibilities there are in the way of different combinations, and the varied phenomena, thereby rendered possible. I will presently describe some of the typical cases.

In the above it has been assumed that the reaction of B variety is opposite to that of A. As previously mentioned, in working with a silver receiver I found it, when fresh, exhibiting at first a diminution and, subsequently, an increase of resistance. The anomalous action may be explained by supposing the normal fresh silver Ag to be positive, and the radiation product Ag′ negative. These two varieties would thus give rise to opposite reactions. To justify the assumptions made above, it became necessary to obtain by some other means a variety of silver Ag′, analogous to the hypothetical negative variety.

Two Varieties of Silver

After many unsuccessful attempts, I at last obtained a variety of silver which gave a moderately negative reaction (increase of resistance). Silver chloride was first precipitated by the addition of dilute hydrochloric acid to silver nitrate solution. The precipitate was then reduced to metallic silver by zinc filings, the excess of zinc being dissolved off by the action of HCl. This form of silver gives a negative reaction. Direct precipitation of silver produced by dipping a piece of zinc in $AgNO_3$ solution gives a positive variety. The negative product Ag′ is perhaps better formed at relatively low temperatures; for the products obtained on certain warm days, the thermometer registering 27° C. were very feebly negative, and passed into the positive state after an interval of twenty-four hours. But on cold days (temperature=22° C.) the products obtained were stable. I have specimens which have kept the negative property unimpaired for nearly three months. The negative property is not due to any accidental impurity, for pure silver obtained by Stas' method also gave the negative reaction. The negative reaction may, however, be supposed to be due to a thin film of chloride formed during reduction. I washed the Ag′ with dilute ammonia, then with water, and, after drying, the result was still a negative reaction. I then carried out a parallel set of experiments with ordinary silver filings. Two separate quantities were taken; one was shaken with only HCl, the other was mixed with zinc filings, and the excess of zinc was dissolved off by HCl; the two specimens were then washed and dried. Both gave the positive reaction of ordinary silver. The above experiments are interesting for the production, by chemical means, of an allotropic variety analogous to the transitory radiation product.

There are other differences of electric behaviour between Ag and Ag′; for instance, when made into a voltaic cell, the two varieties give a P. D. of about 0·12 volt. There are several interesting peculiarities about this cell, the consideration of which is postponed to a future occasion.

Electric Reversal

It now remains to be proved that the "radiation product" exhibits a change of sign of electric touch. The sensitiveness of certain substances belonging to each of these two classes is very great, and the reversed action is likely to be masked by the stronger normal action of the still unconverted portion of the substance. It however occurred to me that if slightly sensitive substances were taken, then the direct and reversed actions were likely to be obtained with less difficulty. For this reason I took for my first experiments arsenic, which is moderately negative.

" *Observations with Arsenic Receiver.—Experiment I.*—A receiver was made with freshly powdered arsenic; the critical distance was found to be 25 cm.; that is to say, when the radiator was moved from 1 to 25 cm. there was always produced an increase of resistance, while beyond this distance there was a diminution of resistance; the critical distance, 25 cm., may therefore be taken as an approximate measure of the negative character of the specimen. As has been said before, if through any cause the substance becomes more negative, the critical distance will be increased; but if the substance tends towards the positive direction by becoming less negative, then the critical distance will be decreased. The receiver was now continuously subjected to radiation for ten minutes. After this it was found that the receiver gave a diminution or positive reaction, even when the radiator was brought close to the receiver. The action of radiation has thus reversed the sign of electric touch.

Experiment II.—Any arbitrary length of exposure labours under the defect that what is observed is the final effect, the intermediate ones passing unnoticed. In order to observe the intermediate effects, a very laborious series of observations is necessary. The experiment was therefore modified in the following manner:—A fresh receiver was subjected to radiation, and observations at intervals of fifteen seconds were taken to test the nature of the reaction of the sensitive substance. The first action of radiation on the fresh specimen was a great increase of resistance, so very great that the current was reduced to zero; it was no longer possible to make any further observation without re-establishing the current. This was done by a very gradual increase of pressure, effected by means of a fine micrometer screw which moved the compressing electrode in a perfectly parallel manner. There should be no jarring motion, as mechanical disturbance was found to break up the complex atomic aggregation in the radiation product. During eight minutes of exposure the receiver continued to exhibit an increase of resistance, after which the substance became positive, being converted to the B state; this positive state lasted for a minute under exposure to radiation, then there was a reversal to the original negative state, as if the structure so laboriously built up suddenly gave way. Subsequently there were series of reversals, the specimen becoming more and more inert, and, after an exposure of about thirty minutes, the sensitiveness was practically lost.

The curve given below represents approximately the results of the experiment. During certain periods the substance became so nearly neutral that it was difficult to interpret whether the substance was positive or negative. The lower halves of the curve represent the negative and the upper halves the positive states, and the corresponding numbers represent, in minutes, the duration of these states.

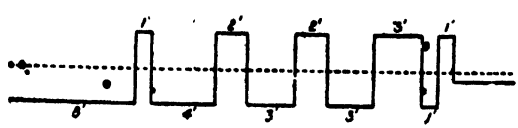


Fig. 23. Electric Reversal Curve.

Radio-molecular Oscillation

It was said that, owing to molecular reversals due to radiation, there should be a corresponding series of electric reversals. In this investigation it is essential that the substance examined should be completely protected from all disturbances, such as mechanical vibration and only subjected to the action of radiation. The experimental difficulties are very great. If we take a strongly sensitive positive substance—say iron, the effect of the first flash of radiation (a diminution of resistance) is very great, and the subsequent relatively feeble reversal effects, unless carefully looked for, are liable to pass unnoticed. After the first adjustment, the receiver should on no account be touched, as mechanical jars are found to undo the effect of radiation. Though by special care the mechanical jars could be reduced to a minimum, yet it appeared advisable to devise appropriate means by which the necessity of touching the receiver for subsequent adjustments is altogether avoided. The method adopted to this end varies with individual cases. In the case of arsenic, for example, the action of radiation is often to produce a very great increase of resistance, and thus convert the substance into a non-conductor. The pressure has therefore to be so adjusted at the beginning, that the substance can never become altogether non-conducting; the receiver is thus absolutely free from all effects, except those which are to be observed—*viz.*, the effects due to continuous action of radiation. The time of exposure is accurately measured by counting the individual flashes of radiation, due to interruption of the primary current in the Ruhmkorff coil by a tapping key. The conductivity of the substance at a given moment is inferred from the deflection of the galvanometer in circuit with the receiver. When feeble radiation is used, it takes an inconveniently long time to obtain reversals; there is, besides, a tendency of self-recovery in the receiver. In order to expedite the reversals, the incident electric radiation is made very strong.

Before entering into the details of the results obtained, I will say a few words about the principal types likely to be met with. We may have the following :—

I. Substances in which the B state is unstable under the given conditions; the B state will therefore only persist during the action of radiation, the substance relapsing into the original condition on the cessation of radiation. Two cases are possible (i) when the substance is positive, (ii) when the substance is negative.

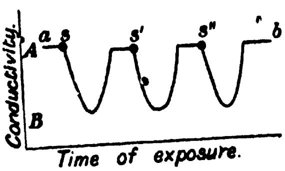


Fig. 24. Curve for Potassium.

The latter case is exemplified by potassium. In the above curve (fig. 24), A and B represent the two molecular states. The substance being negative, A is more conducting; *a* represents the conductivity of the fresh specimen; the thick dots S S′ . . . the individual flashes. It is seen that the effect of radiation is to produce a sudden diminution of conductivity, due to the transient formation of B variety with its diminished conductivity. The substance, electrically speaking, is highly elastic, and it exhibits automatic recovery on cessation of radiation. With the majority of substances, however, self-recovery is only possible when the narrow limit of elasticity is not exceeded.

II. In this class the radiation product is somewhat stable; the successive conversions from A to B and from B back to A are supposed to be complete. Probably there is no substance which exhibits this action in a perfect manner, but there is an approximation to this condition in the case of magnesium, which under proper adjustments shows successive complete reversals for a long time. The substance, however, after a time exhibits the effect of fatigue.

The curve given in fig. 25 clearly exhibits the reversals; it also explains the behaviour of magnesium noticed in my last paper, which appeared very curious at the time. " It is sometimes possible to so adjust matters that one flash of radiation produces a diminution of resistance, and the very next flash an increase of resistance. Thus a series of flashes may be made to produce alternate throws of the galvanometer needle."

The receiver was so adjusted as to give a deflection of five divisions. The first flash of radiation produced

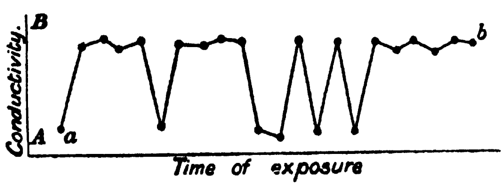


Fig. 25. Radio-molecular Oscillation Curve for Magnesium.

an increased deflection of 90 divisions (magnesium having a positive electric touch); the second flash produced a further deflection of five divisions, the third flash produced a *negative* deflection of five divisions, the fourth flash produced +5, the fifth flash gave —90 divisions, and the sixth flash a deflection of +90. The reversals followed each other almost regularly, till the substance became insensitive.

III. Lastly, there may be a class of substances where the conversion from one state to the other is not complete. Here, again, we get two sub-divisions, owing to the distinction between positive and negative substances.

Taking first the case of a positive substance (see fig. 26 (β)), the original conductivity of which is represented by *a*; the action of the first few flashes of radiation would be to produce a great increase of conductivity by the formation of B variety; the next flashes

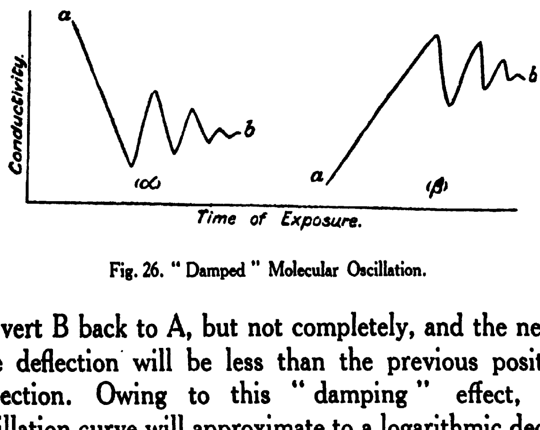


Fig. 26. "Damped" Molecular Oscillation.

convert B back to A, but not completely, and the negative deflection will be less than the previous positive deflection. Owing to this "damping" effect, the oscillation curve will approximate to a logarithmic decrement curve. After a series of reversals the oscillation dies away, and the substance becomes almost inert. A glance at the hypothetical curve β shows that at the inert stage, *b*, *the substance as a whole is more conducting than in the fresh condition a* (see figs. 27, 28).

The opposite should be the case with negative substances (fig. 26α).

Fig. 27 exhibits the actual curve obtained with a (compound) positive substance.

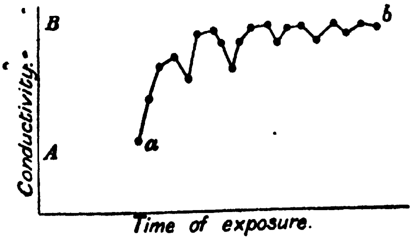


Fig. 27. "Damped" Oscillation Curve for a Positive Substance.

It is remarkable for its regularity. The next figure (fig. 28) gives the curve for iron. The first diminution of resistance is too great to be properly represented in the diagram. Here we have the same type as in the previous case; *the inert stage, b, is also more conducting than a;* (compare with fig. 26 β).

IV. I will now consider the case of a negative substance exhibiting damping; arsenic will be taken as an example where the damping is not so great as in the case of iron. Fig. 29 represents the actual curve obtained with arsenic (compare with the hypothetical curve for a negative substance, fig. 26α). It will be observed that *the negative substance in the fatigued state is, on the whole, less conducting than in the fresh condition,* as we were led to expect from the hypothetical curve.

It will also be seen that the oscillations are fairly regular towards the end. The curves given in figs. 28 and 29 are those obtained with specimens immediately after they were set up. Had I given them a period of rest to allow the particles to get properly settled, I would have got curves even more regular. It is, however, evident that in substances exhibiting

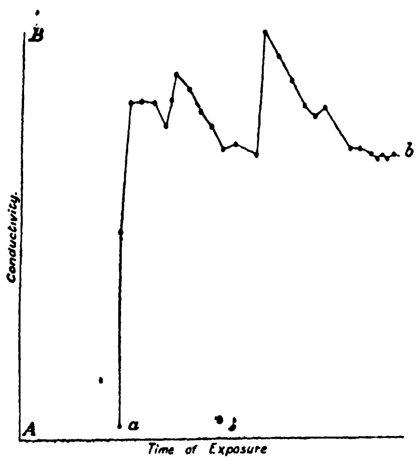


Fig. 28. Curve for Iron.

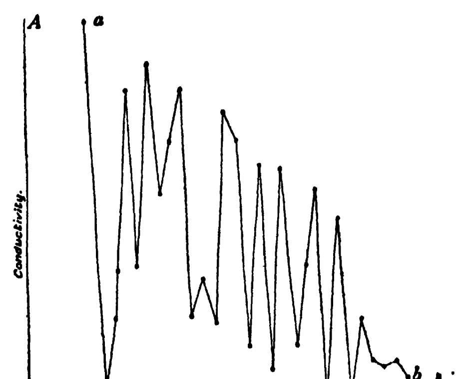


Fig. 29. Curve for Arsenic.

damping, two opposite electric effects are induced in fatigued specimens; the positive becomes on the whole more conducting and the negative less conducting than in the fresh condition. At the inert stage the rate of mutual conversion from one state to the other probably becomes equal, and the apparent fatigue is thus not due to the absolute want of sensitiveness of the constituent varieties, but to the opposite reactions of A and B balancing each other.

We may now apply some further crucial tests to verify the suppositions made above.

Restoration of Sensitiveness to a Fatigued Substance

It was said that the inertness of the substance, after long exposure, is due to the presence of a relatively large amount of strained B variety. It therefore follows that if by any means we can transform B into A, then after such a transformation there ought to be a restoration of the sensitiveness. It has also been stated that the B variety under ordinary circumstances is less stable than A. If now we apply a disturbing cause which is unilateral in its action—that is to say, if it converts B into A and not A into B—then such a disturbing cause will re-sensitise the fatigued substance.

Effect of Mechanical Disturbance.—Of the unilateral actions, mechanical vibration is one; for it is known that by the action of friction a substance may pass from one modification to another in one direction only. Thus the change of monoclinic into rhombic variety of sulphur is hastened by scratching with a glass rod, but the change does not take place in the opposite direction. We may now apply the crucial tests. Mechanical vibration will transform B into A, and with positive fatigued substances this should produce an *increase* of resistance (as A is less conducting than B); with negative substance the same disturbance ought to produce a *diminution* of resistance.

Effect of Heat.—There are other methods by which the B variety may be transformed into A; the more subtle molecular disturbance due to heat may be expected to be even more effective in producing the transformation. Here too, the crucial test is that by slight heating the fatigued positive substance ought to show an increase of resistance, and the negative substance a diminution of resistance. The two following curves (figs. 30 and 31) confirm my anticipations in a remarkable manner.

Effect of Heat and Mechanical Disturbance on a Positive Fatigued Substance.—I shall at first deal with the curve for iron. At the end of No. 28 curve, the substance was left in the inert stage *b*. While in this state, the receiver was heated to a slight extent. Observe in the dotted portion of the curve the sudden fall of conductivity (see fig. 30). I should state here, that, though the fall has been indicated by a straight line, as representing the somewhat sudden fall of conductivity, I sometimes noticed on careful inspection a slight oscillatory movement of the galvanometer spot during this process. The significance of this I will notice on a future occasion. The ultimate effect of slight heating (excess of heat produces other complications) is the restoration of the original reduced conductivity. If the application of heat transforms B into A, we may expect the substance to regain its sensitiveness, which it lost in the fatigued stage *b*. The receiver was now exposed to radiation, and it at once responded, exhibiting almost its original sensibility. Observe how the subsequent portion of the curve is a repetition of the curve No. 28, and how the substance arrives at the second fatigued state *b′*. To observe the

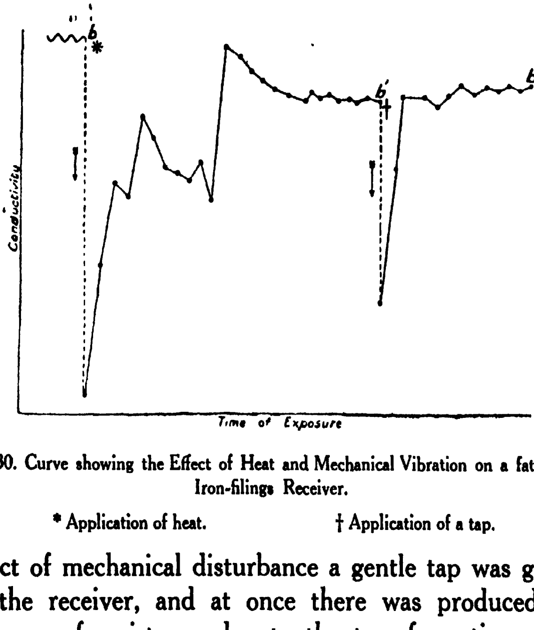


Fig. 30. Curve showing the Effect of Heat and Mechanical Vibration on a fatigued Iron-filings Receiver.

* Application of heat. † Application of a tap.

effect of mechanical disturbance a gentle tap was given to the receiver, and at once there was produced an increase of resistance due to the transformation of B into A, the receiver regaining its sensitiveness by the transformation. The action of radiation was continued, and after a few reversals the substance once more arrived at the third fatigued state, *b″*. The process described above could be repeated any number of times.

Effect of Heat and Mechanical Disturbance on a Negative Fatigued Substance

Experiments similar to the above were carried out with an arsenic receiver. From the curve given below (fig. 31) it is seen that the reaction of a negative substance is in every respect opposite to that of a positive substance. It will be noticed that in confirmation of theory, heating or tapping produces restoration of sensitiveness in the first class by an increase, and in the second by a decrease of resistance. I have been able to verify this deduction by observations with nearly a dozen different substances, and have not, so far, come across any to contradict it. It thus appears that tapping restores the sensitiveness not by the separation of the electrically-welded particles (in which case tapping ought to have produced an increase of resistance in *both* the classes of fatigued substance), but by removing the strain in B and thus converting it into A.

The effect of electric radiation is thus to produce re-arrangement of atoms and molecules in a substance;

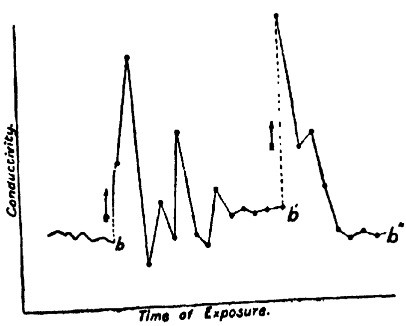


Fig. 31. Curve showing the Effect of Heat and Mechanical Vibration on a fatigued Arsenic Receiver.

b Effect of heat. *b'* Effect of tapping.

so does light produce new atomic and molecular aggregation in a photographic plate, a subject to be dealt with in detail in a future paper. Some of my audience at the Royal Institution (January, 1897) may remember my attempt at explaining the action of the so-called coherers (which, perhaps, may be better described as "molecular receivers") by analogy with the photographic action. I had then no proofs for the assertion. I have since been able to obtain experimental evidence that the two phenomena are essentially similar. The coherer may therefore be regarded as a linear photographic plate; since we are more likely to understand the complex photographic action from the consideration of the much simpler action of electric radiation on elementary substances, where the effects are not complicated by secondary reactions, a photographic plate may be regarded as merely an assemblage of "molecular receivers." I hope also to prove that nearly all the detectors of radiation are molecular receivers in reality. The investigation of this aspect of the subject has given me some striking results; they seem to connect together many phenomena which at first sight do not seem to have anything in common. Another interesting question, the consideration of which has for the present to be postponed, is, Why is it that the sensitiveness is so marked in discontinuous metallic particles? In other words, Why is the phenomenon mainly one of skin or *touch*? Is the phenomenon wholly unknown in continuous solids?

The experiments described in the present paper show:—

(1) That ether waves produce molecular changes in matter.

(2) That the molecular or allotropic changes are attended with changes of electric conductivity, and this explains the action of the so-called coherers.

(3) That there are two classes of substances, positive and negative, which exhibit opposite variations of conductivity under the action of radiation.

(4) That the production of a particular allotropic modification depends on the intensity and duration of incident electric radiation.

(5) That the continuous action of radiation produces oscillatory changes in the molecular structure.

(6) That these periodic changes are evidenced by the corresponding electric reversals.

(7) That the "fatigue" is due to the presence of the "radiation product," or strained B variety.

(8) That by means of mechanical disturbance or heat, the strained product can be transformed into the normal form, the sensitiveness being thereby restored.

The method described above of detecting molecular changes is extraordinarily delicate, and is full of promise in many lines of inquiry in molecular physics. It is also seen that the phenomenon of contact sensitiveness, contrary to previous suppositions, is perfectly regular. There is no capriciousness in the response of sensitive substances to the external stimuli, which may be mechanical, thermal, or electric. The curves given above show this; but they fail to give a fair idea of the richness and variety of the molecular phenomena, seen as it were reflected in the fluttering galvanometer spot of light; of the transitory variations—of the curious molecular hesitation at critical times as to the choice of the structure to be adopted, and of the molecular inertia by which the newly-formed structure is carried beyond the position of stability, and the subsequent creeping back to the more stable position. The varieties of phenomena are unlimited, for we have in each substance to take account of the peculiarity of its chemical constitution, the nature of its response to ether waves, the lag and molecular viscosity. All these combined give to each substance its peculiar characteristic curve; it is not unlikely that these curves may afford much information as to the chemical nature and the physical condition of different substances. I am at present trying to arrange an apparatus which will, by means of the pulsating galvanometer spot of light, automatically record the various molecular transformations caused by the action of external forces.

(*Proc. Roy. Soc., Feb.* 1900.)

XIV

ON THE CONTINUITY OF EFFECT OF LIGHT AND ELECTRIC RADIATION ON MATTER

Though the theory of coherence gives a simple explanation of many cases of diminution of resistance in a mass of metallic particles subjected to electric radiation, yet there are other cases which cannot be explained by that theory. If coherence be due to electric welding, it would follow that *all* sensitive particles would exhibit a permanent diminution of resistance; in other words, the action should be non-discriminative and there should be no self-recovery. I have shown, however, in a previous paper, that the effect of radiation is by no means non-discriminative. On the contrary, while its effect on the positive class of substances, *e.g.*, Mg,Fe,Ni, is a diminution of resistance, its reaction on the negative class, *e.g.*, K,Ag′,Br,I, is precisely the opposite, namely an increase of resistance. Further, the conductivity change is not always permanent, since several substances are known which quickly recover and attain their original conductivity on the cessation of radiation, as if a force of restitution were called forth to restore them to their original condition.

I was thus led to suppose that the effect of radiation is to produce a state of molecular strain. Evidences will presently be adduced which will furnish proofs in support of this view.

If a substance is molecularly distorted by the action of an external agent, we may naturally expect that there would be produced changes in the physico-chemical

N 2

property of the substance. As a familiar instance phosphorous is changed from the yellow to the red variety by the action of visible radiation. After the allotropic transformation into the red variety, phosphorus has become chemically less active, insoluble in CS_2, and of higher specific gravity. Similarly its other properties, such as its elasticity, its position in the voltaic series, its electric conductivity, etc., undergo a corresponding modification. An identical molecular phenomenon, seen from different aspects, may thus appear to be diverse. Looking from an electric point of view it is found that the conductivity of red phosphorus is greater than that of the yellow variety. It is thus possible to measure the induced molecular change by measuring the correlated variation of any of the properties described above. The choice of a particular method will be governed by special convenience under given conditions.

It would thus be possible to detect the effect of molecular strain induced by visible or invisible radiation by the following more or less sensitive methods. It is to be borne in mind that the effect of radiation is almost confined to the skin or outer layer of the substance.

(1) Method depending on the variation of the adhesive or cohesive power of a substance, *e.g.*, in a daguerreotype plate, the mercury vapour adheres by preference to the light-impressed portions only. Images may in a similar manner be developed by water vapour.

(2) Method depending on the variation of chemical activity undergone by the strained substance, or the method of photographic development. The acted and unacted portions are differ-

ently attacked by the developer. The action is not altogether independent of the effect described below.

(3) Method depending on the variation of electric potential, by which an E. M. F. is produced between the acted and unacted portions of a substance originally iso-electric.

(4) Method depending on the conductivity variation produced by the strain.

In the following investigations I shall employ specially the two last methods, and hope to demonstrate the fundamental unity of effects of visible and invisible radiation on matter. The subject is very extensive, and I propose to deal with it, as briefly as is compatible with clearness, in the three accompanying papers :—

I. "On the Continuity of Effect of Light and Electric Radiation on Matter." In this paper various experimental methods and results will be given, which can only be explained on the supposition that the observed effects are due to strain.

II. "On the Similarities between Mechanical and Radiation Strains." If the effects as described above are really due to strain, then similar results might be brought about by artificially producing strain in regard to which there can be no possibility of doubt, such as strain produced by mechanical means.

III. "On the Strain Theory of Photographic Action." Having shown the strain effect due to light, I will show how some of the obscure phenomena in photography receive a simple explanation on the above theory.

Effect of Electric Radiation

1. *Method of Conductivity Variation*

This method is specially suited for studying the effect of electric radiation on discontinuous particles. Since the action of radiation is one of surface, the larger is the superficial area the greater is the result; it is evident that loose particles expose a large surface to the incident radiation. Moreover, as the effective total resistance of the mass of particles is due to resistances of *surface* contacts, any change induced in the surface layers will cause great variation of the total resistance. In a continuous solid, on the other hand, only a comparatively thin molecular layer on the surface is acted upon; but this has little effect on the conductivity of the mass in the interior, protected by the outer conducting sheet. A slight conductivity variation can, however, be detected if the continuous solid takes the form of an extremely thin layer. I shall presently show that for the detection of molecular strain in a continuous solid the electromotive variation is the more suitable.

It has been stated that in the positive class there is produced a diminution, and in the negative an increase of resistance. These opposite reactions seem at first difficult to understand, but about their reality there can be no doubt. In another paper to be shortly communicated, I shall give an account of an independent inquiry in which the positive, the neutral, and the negative classes of substances are differentiated by their characteristic curves. From the strongly positive substance like Fe, Mg, to the pronounced negative like K, there are numerous gradations. In silver we have a material which is almost on the line of demarcation; it passes easily from one condition to another under the influence of external variations.

2. *External Change*

If the response, positive or negative, is really an expression of some changed molecular condition, we may expect it to be modified not only by the chemical nature of the substance, but also (1) by previous history of the substance, (2) by temperature, and (3) by pressure.

Influence of previous history.—As regards the first, I have already shown in a previous paper that a substance strained by radiation often exhibits opposite or reversal effects. Freshly powdered particles often show erratic results, but the effect becomes consistent after annealing, which also increases its sensibility evidently by increasing the molecular mobility. The improvement in sensitiveness often obtained by shaking of the particles is no doubt due to the same cause. In the various types of molecular receivers, whether responding to electric radiation, light, or mechanical vibration, similar effect is observed. The receiver generally speaking, improves gradually with working; but after long-continued action it gets overstrained and exhibits fatigue.

Influence of temperature.—As regards temperature, I have often found that on excessively cold days the receivers exhibit a diminution of sensibility, which becomes restored by warming. Various reactions which were very strongly exhibited in the warm climate of India, I found to be much diminished in Europe. Cautious application of heat often increases, not only the sensibility, but also the power of self-recovery.

High temperature, however, produces erratic behaviour by causing violent molecular disturbance.

Influence of pressure.—Pressure also has pronounced effect on molecular response. Moderate increase of pressure increases the sensibility, but too great an increase may cause a loss of sensibility. In substances which are nearly neutral, pressure variation may even cause reversal of response.

The same receiver may, owing to some obscure molecular modification, exhibit a response opposite in sign to the normal. But under continued stimulation of radiation, the abnormal response becomes converted into the normal. Parallel instances will also be noticed in the case of response to mechanical stimulus and to light. It is thus seen how the response is dependent on the molecular condition, and how a change of this condition may culminate in a reversal of response, say, from a diminution to an increase of resistance. The nature of the chemical substance, the molecular condition, the intensity and duration of radiation, the pressure, the temperature, and even the electromotive force acting on the circuit, are the factors instrumental in the determination of the resultant response. I have already shown how the cumulative action of continuous radiation may produce molecular reversal. There may thus be one or more reversals.

3. *Recording Apparatus*

In the following investigations, it is necessary to observe the conductivity or the electromotive variations, induced by external stimulus of various durations. It is also necessary to note the time-relations of direct and after-effects. The conductivity and electromotive variations can be deduced from the observed deflections of the galvanometer. When these are rapid, the observation requiring great alertness becomes very fatiguing. This difficulty is still greatly accentuated when simultaneous time-observations have to be taken. It thus becomes necessary to have at least two observers; the process of observation is very tedious, and the accumulation of results extremely slow. But in the apparatus now to be described, the mode of procedure has been very much simplified, affording facilities for quick and accurate record of responsive reactions.

The moving platform of the apparatus carries a squared paper (divided into $\frac{1}{10}$ inch) on which the record is made. The platform moves uniformly by clock-work, and the rate of travel of the paper may be

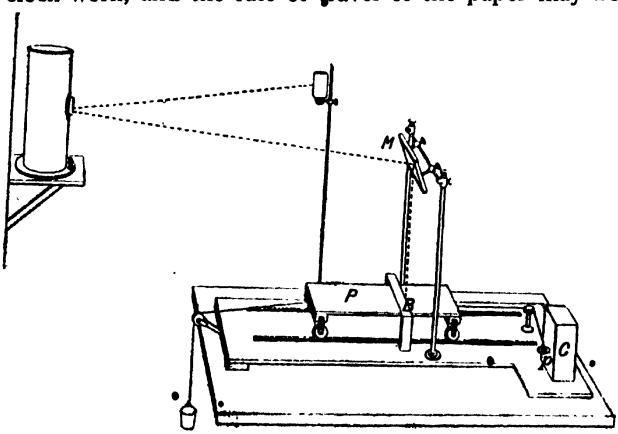


Fig. 32. The Recording Apparatus. P is the platform moving on rails and carrying the squared recording paper. C, the clock-work. M, the mirror to reflect the galvanometer spot of light on the platform.

roughly adjusted by means of different-sized pulleys, or more finely by the clock-work governor. The usual rate is 1 inch in 30 seconds, and one small division of the paper measured horizontally is thus equal to 3 seconds. But very much quicker or slower rates may easily be obtained by means of the different-sized pulleys. The spot of light from the galvanometer is thrown down on the paper by an inclined mirror. The movement of the galvanometer spot takes place at right angles to the direction of motion of the paper. There is a guide rod at right angles to the motion of paper, along which the recording pencil is moved. The excursion of the galvanometer spot can thus be easily followed with a pencil, and it is quite easy to do this, when the fluctuation period is about 2 seconds. In the experiments to be described, this period varied from 2 seconds to several minutes. A curve is thus directly obtained, with conductivity or electromotive variation as ordinate, and the time as abscissa. The curves given in the accompanying papers are exact copies of the direct records.

4. *Transition of a Molecular Receiver from Non-recovering to Self-recovering Condition*

When a substance is strained by radiation there is produced a sudden variation of conductivity. The substance automatically recovers from the strained condition (1) if it has not been overstrained by an excessive stimulus, or (2) if its electric elasticity is very great. I have found, in general, that after careful adjustment of the receiver it exhibits tendency towards self-recovery, if the intensity of incident radiation is not too strong. In the case of substances which are, electrically speaking, highly elastic, such as K, there is an automatic recovery even after strong stimulation. The difference exhibited by various substances in regard to self-recovery is one merely of degree. I give below typical cases which exhibit the gradual transition from so-called non-recovery to complete self-recovery.

The galvanometer used is a dead-beat D'Arsonval of moderate sensitiveness. The receiver was appropriately fixed on a heavy base. This was supported on one or two sets of pneumatic tyres so as to protect the sensitive receiver from mechanical vibration.

Positive Type.—In fig. 33 (*a*) is shown the effect of radiation on Fe_3O_4 when cold. Only the upper portion of the curve is given; the flash of radiation produced a deflection of the galvanometer of sixty-four divisions.

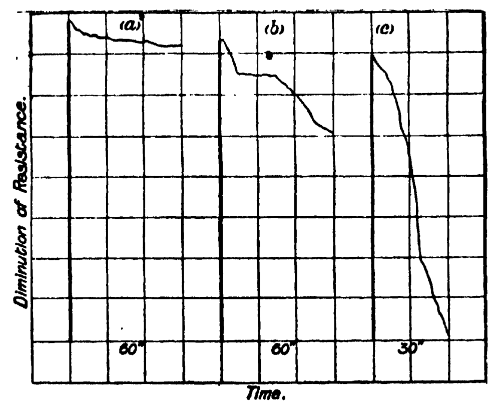


Fig. 33. Different stages in the evolution of a Molecular Receiver from a non-recovering to a self-recovering condition. The substance used is Fe_3O_4, representing positive type, which exhibits a diminution of resistance under electric radiation. (*a*) the so-called non-recovery, really a case of very slow recovery; (*b*) the same slightly warmed, exhibiting a partial and arrested recovery; (*c*) the same with increased molecular mobility, recovery in 30″. In this and in the following, thick line represents response to radiation, thin line exhibits recovery.

It will be observed that it had recovered to the extent of three divisions in the course of 60 seconds; if the rate of recovery had been uniform, there would have been complete recovery in about 21 minutes, but in the later stages, the recovery is very slow. In (*b*) is shown the effect of increased molecular mobility due to cautious warming. There was now semi-recovery in 60 seconds; the quickness of recovery went on improving, and after a while the recovery was completed in 30 seconds.

Negative Type.—Fig. 34 exhibits the effect on the negative type as exemplified by Sn and Pb coated with Br. It appears that warmth is favourable to quick recovery; for in India with Pb coated with Br the self-recovery was obtained with the greatest ease. In the colder climate of England it takes a longer time for

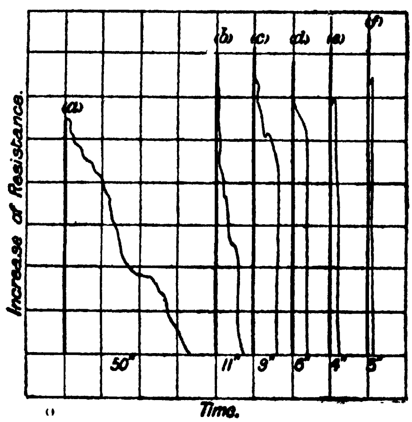


Fig. 34. Self-recovering Receiver exhibiting negative response (increase of resistance under radiation). (*a*), (*b*), (*c*), and (*d*) are the different stages of quickness of recovery in a brominated tin receiver; (*e*) and (*f*) are the records of a brominated lead receiver.

the receiver to become adjusted to the condition of self-recovery. At first the flash of radiation produces a sudden increase of resistance, from which there is no immediate recovery, but an inspection of the galvanometer spot at once makes it evident that some internal struggle has been going on; the spot trembles, as if to overcome some internal friction; the substance then exhibits a sudden recovery. After these preliminary molecular adjustments the recovery becomes perfectly automatic and instantaneous. Each flash of radiation then produces a responsive galvanometer twitch, *immediately* followed by recovery.

Some of the stages are well seen in the curves given. In (*a*) the recovery takes place in 50 seconds; in (*d*) in only 6 seconds; (*e*) and (*f*) show recovery in lead coated with bromine. The recovery gradually became very quick, from 4 seconds to 3 seconds; after that it was too quick for record.

In all the above cases it will be noted that the curve of recovery is convex to the abscissa; that is to say, it is at first very rapid, but in the later stage it becomes relatively slow.

5. *A Self-recovering and Metrical Receiver*

The most perfect type of self-recovering receiver that I succeeded in constructing was made of the strained variety of silver described in a previous paper. It was there shown that this variety of silver exhibits, under the action of radiation, an increase of resistance. I had with me a portion of this variety prepared more than a year ago, and it is probable that time had improved its quality. I made with it a receiver consisting of 3 mm. thickness of the powder between two electrodes; the pressure was adjusted by means of a micrometer screw which pressed one of the electrodes. The applied electromotive force was 0·4 volt, and the resistance of the receiver was equal to 20 ohms. The receiver showed the usual increase of resistance with a tendency to self-recovery. In about half an hour it began to exhibit the most perfect self-recovery, and for the next 3 hours of continuous work it went on giving an extraordinary consistency of response.

The intensity of incident radiation was varied by changing the distance of the radiator. In fig. 35 are given responses to individual flashes at distances of 40 and 15 cm. It will be seen that the effects are very

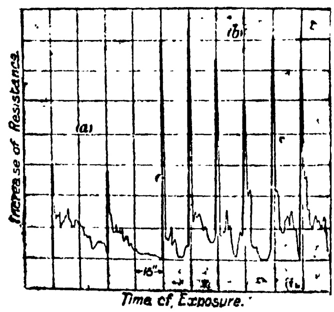


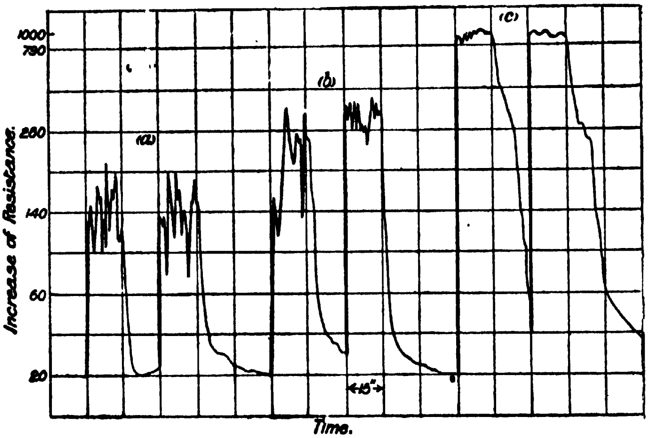
Fig. 35. Transient increase of resistance in an Ag′ receiver due to single flashes of radiation. In (a) the radiator was at a distance of 40 cm.; in (b) the distance was reduced to 15 cm. Thick lines represent the effect of radiation, thin lines represent the recovery.

consistent, the occasional variation being probably due to some of the oscillatory sparks not having been as efficient as the others.

Certain analogies with the phenomena of Phosphorescence and Thermo-luminescence.—A remarkable phenomenon will be noticed in the recovery curve. It will be seen that the complete recovery is effected after a series of minor oscillations. In other words, there seems to be an after-vibration which persists for a time in substances subjected to radiation. This is very suggestive in regard to a not altogether different after-effect of light in the fluorescent and phosphorescent bodies. In the case of Ag′ receiver, owing to its molecular mobility, the recovery is automatic. But in the case of so-called non-recovering substances, the strain persists for a considerable time; the recovery can, however, be hastened by removing molecular friction through gentle heating. In connection with this, I will quote an interesting observation previously made. In an iron receiver strained by radiation there was quick recovery after heating, and careful inspection showed a slight oscillatory movement of the galvanometer spot during the process. Here the strain produced by radiation remained latent to be released by heat. In the phenomenon of thermo-luminescence, the strain effect of light also remains latent till set free by the application of heat.

Effect of Continuous Radiation.—Still more interesting are the superposed effects of a series of flashes of radiation. The first flash produces a certain molecular distortion, attended with conductivity variation, from which it tends to recover. This force of restitution will be shown to increase with increasing distortion. Now if, before the substance has recovered from the first shock, a second flash be superposed, it will produce further distortion; but the effect will not be quite so strong, inasmuch as the force of restitution is increasing. Thus a series of superposed flashes will produce a limiting effect, which is kept balanced by the force of restitution. Under increased intensity of radiation, the balancing position is at a higher level. The after-effect, moreover, is more persistent under stronger intensity of stimulation.

In fig. 36 are shown the effects of rapidly succeeding flashes of radiation caused by the spring vibrator of a



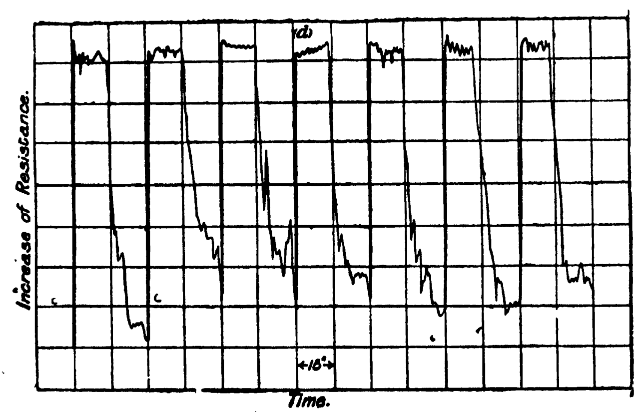


Fig. 36. Variation of resistance (deduced from diminution of galvanometer deflection) in Ag′ receiver produced by electric radiation lasting for 15″. Distance of radiator in (*a*)=40 cm.; in (*b*)=25 cm.; and in (*c*)=15 cm. In (*d*) is given a series of curves taken after half an hour with the radiator at a distance of 15 cm. The numbers on the left side of the upper curve indicate the absolute value of resistance.

Ruhmkorff's coil: In (*a*) the radiator was kept at a distance of 40 cm.; the radiation was continued for 15 seconds, after which 15 seconds was allowed for recovery. A longer time would have allowed a more complete recovery, but this would have entailed a great loss of time in the long series of experiments contemplated. The recovery is therefore partial, the return curves not exactly reaching the original starting position. The record of response to the source of radiation at a distance of 40 cm. shows that there is a partial recovery between quickly recurring flashes, observed in the fluctuating response about the balanced position. Now when the intensity of radiation is increased by decreasing the distance of the radiator to 25 cm. (see *b*), the strain effect persists for a longer time, and the flashes arrive before the substance can have recovered to any extent; there is thus less fluctuation in the balanced position. The intensity of radiation was further increased by placing the radiator at a distance of 15 cm. (see *c*) the fluctuations now disappeared; and the galvanometer deflection was held rigid as long as the radiation was kept on; in fact, we have here an effect which physiologists describe as "tetanic." On the cessation of radiation there was an *immediate* recovery. It will be noticed how extraordinarily consistent are the succeeding values of response. The resultant effect being due to the additive effects of numerous flashes, an occasional failure of an individual flash is of little or no importance. The series of responses in (*d*) was taken after half an hour; it will be noticed how very consistent they are among themselves and how similar to those in (*c*), showing that even after half an hour's continuous work there had been but little fatigue with the attendant change of sensibility.

Relation between the Intensity of Radiation and the Conductivity-variation.—The resistance of the receiver being not very large, the external resistance of the shunted galvanometer and of the cell are not negligible in comparison; the change of deflections is, therefore, not proportional to the variation of resistance. To interpret the absolute values of the deflections, a resistance box was substituted for the receiver, keeping the rest of the circuit just as before. In this way the absolute values of the resistances corresponding to particular deflections were found. Some of these are given on the left-hand side of fig. 36.

The galvanometer deflections, when the radiator was at distances of 40, 25 and 15 cm., were 23, 33 and 42 divisions respectively. Owing to the comparative steadiness of the last two deflections there is no uncertainty about them; but on account of the fluctuation in the deflection when the radiator is at a distance of 40 cm., it is difficult to find the exact value of the deflection; the mean of the various deflections gives twenty-three divisions. The absolute values of resistances corresponding to these deflections are 180, 380, and 1020 ohms. The original resistance being 20 ohms, the *variations* due to the different radiation intensities are 160, 360, and 1000 ohms.

The intensities of radiation at the above distances may approximately be taken as proportional to $\frac{1}{40^2}, \frac{1}{25^2}, \frac{1}{15^2}$, or as 14 : 36 : 100. The corresponding molecular effects as measured by the increase of resistance are found to be as 16 : 36 : 100.

It will thus be seen how accurately the indications of the Ag′ receiver measure the intensity of radiation. Further progress in the study of different phenomena connected with electric radiation has been seriously hampered owing to the want of means for measurement of intensity of electric radiation. But this difficulty, as will be seen from the above, is not insuperable.

The strict proportionality of molecular effect can be taken as true only through a limited range. From the results of various experiments, into the detail of which I can not at present enter, it appears that, generally speaking, the curve of response (with molecular effects as ordinates, and the intensities of stimulus as abscissæ) is not a straight line. It is at first slightly convex, then straight, and in the last part concave. It is only in the second part that the curve is approximately straight.

In considering the effect of electric radiation in changing the conductivity of the particles, no explanation can be regarded as complete, unless it explains not only the diminution, but also the increase of resistance; the phenomenon of automatic recovery and the opposite effects exhibited by the same receiver under different molecular conditions, have also to be explained. The increase of resistance of the Ag′ receiver and its instantaneous recovery are directly opposed to the theory of coherence.

The state of balance between the effect induced by radiation and the force of restitution on the one hand, and the different equilibrium positions with different radiation intensities on the other, point to the phenomenon being due to molecular strain produced by radiation.

Fatigue of the Receiver.—I wished to trace the gradual appearance of fatigue in the Ag′ receiver, and for this purpose kept it acted on with slight intermissions for nearly 3 hours. At the end of that time it began to show unmistakable signs of fatigue. Fig. 37 shows

Fig. 37. Fatigue and reversal in the Ag′ receiver. Thick lines represent the effect of radiation, and dotted lines the recovery. Observe in the first three records the incomplete recovery and increasing fatigue. In the fourth, there is produced a reversal (a diminution of resistance instead of the normal increase).

the effect when the radiator was at a distance of 20 cm.; the deflections were now only twenty-one divisions, whereas before this the deflection was thirty-three divisions with the radiator at the increased distance of 25 cm. Formerly the recovery commenced immediately on the cessation of radiation, now there was a short period of hesitation and then it began to recover somewhat slowly. The extent of recovery also grew less and less, and at last the receiver suddenly exhibited the reversal effect, by showing a *diminution* of resistance.

A parallel instance under the continued action of light will be demonstrated later.

6. *Phenomenon of Reversal*

(a) *Effect of Sub-minimal Intensity of Stimulus.*—Another very curious phenomenon met with is the opposite effects of radiation below and above the critical intensity. I have in a previous paper shown that, whereas the effect of radiation of moderate intensity on As is to induce an *increase* of resistance, the effect of feeble intensity of stimulus is to produce a *diminution*. Positive classes of substances exhibit parallel results. The opposite effects of feeble and strong stimulation are exhibited not only under electric radiation, but also under mechanical stimulus (*cf.* p. 204). This result is certainly very curious, but I will show later on that exactly similar effects are produced under mechanical stimulation.

Possibly connected with the above is the following: A receiver subjected to radiation of moderate intensity, often exhibits a short-lived negative twitch immediately followed by the normal response. This is probably due to the fact that it takes some time for the sensitive substance to absorb the whole amount of incident radiation. The first moiety absorbed may thus fall below the critical intensity, and thus gives the preliminary twitch of opposite sign to the normal which occurs later by the absorption of a larger amount of radiation. The response-curve thus exhibits a negative twitch which precedes the normal.

(b) *Reversal due to Overstrain.*—I have also shown that overstrain due to the continued action of radiation gives rise to a reversal of response, the reversal being partial or complete. I give below a curve (fig. 38) for Fe_3O_4 under continuous radiation, where, after the maximum effect was reached, there was a distinct trend towards reversal.

The positive class of substances, the normal response of which is positive or diminution of resistance under moderate stimulation, gives negative response (increase of resistance) under sub-minimal stimulus. This is specially noticeable in a receiver rendered inert by prolonged rest. Annealing makes the response normal, as also previous stimulation. Strong and prolonged stimulation tends to reverse the normal negative response into positive. All these peculiarities of response under electric radiation will also be found characteristically exhibited by other receivers responding to the stimulus of light or of mechanical vibration.

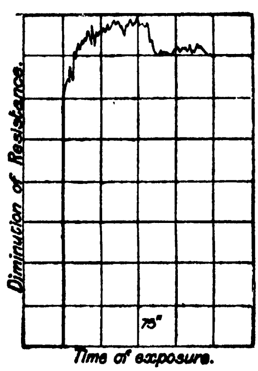


Fig. 38. Tendency towards reversal in Fe_3O_4 receiver under the continued action of radiation. Thick line shows the immediate effect, the thin line the continued effect of radiation. In other cases the reversal is complete.

7. *Physical Nature of the Change*

From the fact that the conductivity variation above described takes place in platinum and other noble metals, and the further fact that the action goes on even when the substance is kept immersed in a protecting medium such as naphtha, it would appear that the observed effect is primarily due to physical strain. By chemical action it is generally understood that the change is irreversible and in one direction. But in the cases of complete self-recovery exhibited by various substances, there is an automatic return to the original condition. It should, however, be borne in mind that, as a result of the strain, the chemical activity of the substance may undergo a change; a chemical action would occur if the strained substance be immersed in a medium for which it has a relatively stronger attraction.

8. *Electromotive Variation produced by Electric Radiation*

In consequence of molecular strain produced by electric radiation a difference of potential would likely be induced between the acted and unacted portions of a substance. A voltaic cell could be made with two plates of similar substance; there would then be no P. D. between the two. But on exposing one of the two plates to the effect of radiation, a difference of potential might be established between the acted and unacted plates. The differential effect, if it exists, could then be detected by a galvanometer or an electrometer. There are, however, many difficulties in rendering this method practical. First of all, in making a voltaic combination, some kind of electrolyte is necessary, but unfortunately all electrolytes are opaque to electric radiation. This difficulty could, however, be obviated to some extent by taking an electrolyte which is almost a non-conductor (e.g., amylic alcohol) so as to be partially transparent to electric waves. The second difficulty is, however, far more serious for owing to the diffuse action of the comparatively long electric waves it is impossible to shield one plate while exposing the other. If both the plates are equally acted upon, there would then be no electromotive *variation.* It was only after the conclusion of another line of investigation on the electromotive variation produced by mechanical stimulus that a clue was obtained to overcome the difficulty. I then learnt that the effects of the same stimulus on two pieces of the same metal, forming a voltaic element, are not the same if the molecular conditions of the two are different. Under such a condition a P. D. exists between the two, and stimulation of both causes a variation of the existing electromotive force.

I therefore expected to detect the effect of electric radiation by an induced *variation* of the original electromotive force. And if the effects are at all parallel to those found in the conductivity variation method (as diminution or increase of resistance) the corresponding effects might be observed by a diminution or an increase of the existing electromotive force.

In carrying out experiments to verify the above suppositions, I found my anticipations to be justified. I at first made a cell by taking two varieties of silver. A piece of cotton wool moistened with amylic alcohol was placed in a glass tube. Ag and Ag′ were placed on opposite sides of the moistened cotton, thus forming a voltaic element, the amylic alcohol acting as the electrolyte. Two electrodes compressed the powder, till a current was observed to flow. As in the case of receivers for exhibition of conductivity variation, a careful adjustment of pressure is necessary for obtaining the best result. In order that the effect observed might be purely due to electromotive variation and not to the variation of conductivity, the cell was connected with a capillary electrometer. Owing to the opacity of the electrolyte the intensity of radiation has to be strong; the radiator was therefore placed at a distance of 6 inches from the cell. The incident radiation induced a responsive variation of the electromotive force. Long continued radiation induced a reversal as observed in the case of conductivity-variation previously described.

I give below the results of three experiments with different combinations :—

	Original E. M. F.	New value after the action of radiation.	Percentage reduction.
I . .	1·26 V.	1·15 V.	9
II . .	0·39 V.	0·312 V.	20
III . .	0·065 V.	0·039 V.	40

I was next desirous of obtaining a continuous record of electromotive changes induced by the continued action of electric radiation. For this purpose I used a galvanometer.

A cell was made, in the way previously described, with two specimens of magnesium powder. Owing to some differences in the two portions there was an initial P. D. of 0·042 V. between the two electrodes. The E. M. F. of the cell was balanced by the potentiometer method, a sensitive galvanometer (with an interposed high resistance) being used as the detector of electromotive variation. Fig. 39 (*a*) shows the deviation from the balanced position by radiation which nearly reduced the potential difference to half its original value. A second experiment [see (*b*)] gave almost identical results.

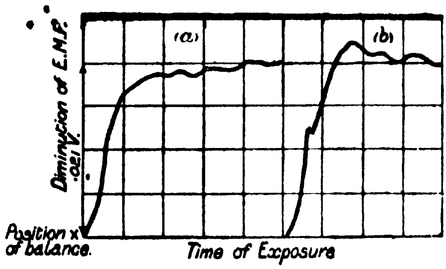


Fig. 39. E. M. variation in a Mg receiver. The original E. M. F. was 0·042 V. This was reduced to 0·021 V. by electric radiation.

It is thus seen that the response-curve by electromotive variation under electric radiation is similar to that obtained by the method of conductivity variation.

It has been shown that there is a recovery when the range of electric elasticity of the substance is not narrow, or when the strain is not too great; that on subjecting the substance to the continued action of radiation there is a limiting effect; that too long continued action tends to produce an electric reversal; that too feeble an intensity may give rise to a response of opposite sign to that of the normal. We shall next investigate whether visible radiation produces similar results.

Effect of Light

The molecular effect due to visible radiation may as in the previous case, be detected by the method of conductivity or electromotive variation. That light does produce conductivity variation is seen in selenium. I have also succeeded in detecting the effect of light in producing variation of contact resistance in a galena receiver. One and the same receiver responded in the same way when alternately acted on by visible and invisible (electric) radiation. The peculiarities of this universal radiometer were in every way similar to those of detectors for electric radiation.

It is, however, more satisfactory to study the effect of light in producing electromotive variation. Becquerel, Minchin, and others have shown that light produces an electromotive variation in a photo-electric cell. Like electric radiation, the effect of light is not confined to any particular metal or groups of metals, but all metals exhibit an electromotive variation under its action. Two opposite effects are likewise shown; in some cases the potential is raised, in others, the potential is lowered by the action of light.

I now proceed to show the remarkable similarity of the curves of response produced under electric radiation and under light. For the photo-electric cell I used two silver strips fastened by solid paraffin on two sides of a glass plate. The front surfaces were exposed to bromine vapour. The two strips formed the two plates of the photo-electric cell, the electrolyte being common tap-water.

If the two strips are exactly similar, then there is no P. D. between them, and the effect of light on either of the strips is the same. When both the plates are illuminated, there is then no resultant effect. But if the two plates are slightly different, then the effects on the two are not the same. An electromotive variation is induced even when both the plates are exposed to light.

9. *Effect of Short Exposure to Light*

In fig. 40 (*a*), is shown the effect of light of 2 seconds duration on one of the two AgBr plates. An incandescent gas-burner was placed at a distance of

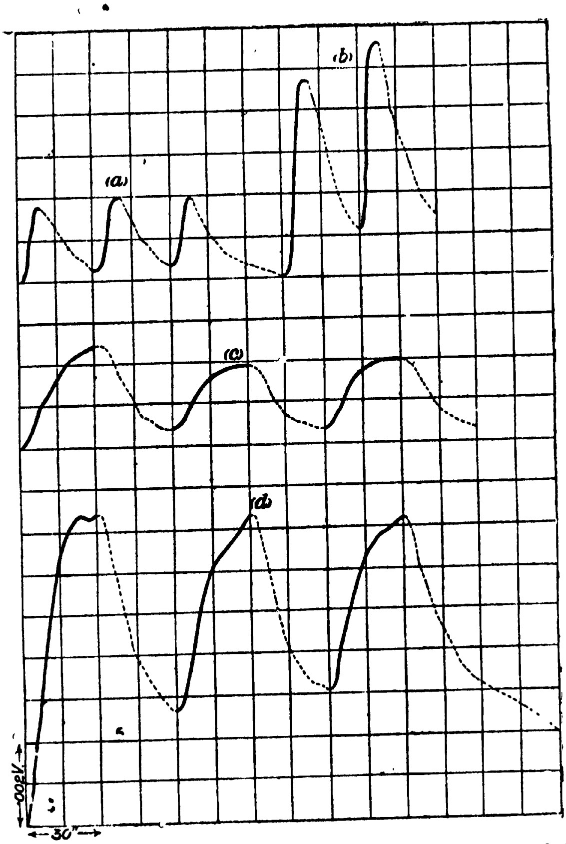


Fig. 40. Electromotive variation in AgBr cell due to the action of light. Ordinate represents E. M. variation, and abscissa the time. Thick lines represent the effect of light and dotted lines the recovery. (*a*) and (*b*) represent the effect of exposure to light for 2 seconds. The distance of source of light in (*a*) = 12 inches; in (*b*) = 6 inches. (*c*) and (*d*) represent the effect of continuous light for 30"; distance of source of light in (*c*) = 18 inches; in (*d*) = 9 inches.

12 inches. Previous maintenance of the plates in the dark enhances the sensitiveness; the cell then responds to feeble light emitted by a candle. The similarity of responses to light and electric radiation is very remarkable (*cf.* fig. 35). The recovery curve is also convex to the abscissa. The time allowed for recovery was not sufficient to bring the substance back to its original condition. The successive starting-points are therefore slightly ascending. In the last curve in the series (*a*) sufficiently long time was allowed, and the substance completely recovered in about 37 seconds. (*b*) shows the effect of light of about four times the intensity, the source being brought nearer to a distance of 6 inches. The effect is stronger, but not quite equal to four times the effect produced in the last case.

10. *Effect of continuous Action of Light*

Just as in the case of electric radiation, light produces a maximum effect, corresponding to a given intensity. Fig. 40 (*c*) shows the effect of continuous light of 30 seconds duration, the source of light being at a distance of 18 inches. Observe the tendency of the curve to become horizontal when reaching the maximum. (*d*) shows the effect of four times the intensity, the source of light being at a reduced distance of 9 inches. Here, too, the intensity of effect is not quite four times the effect of light at a distance of 18 inches.

11. *Reversal Effects*

With electric radiation it was found that the effect of a flash was sometimes a preliminary negative twitch immediately followed by the normal response. With light, too, it is frequently found, as has also been observed by Minchin, that the immediate result is a transitory negative followed by the normal action. A reversed response is also observed under molecular modification.

If the action of light is prolonged beyond the attainment of maximum effect, a tendency appears towards, or actual reversal.

In fig. 41 is given an interesting series of results showing the growth of fatigue, the different phases culminating in an actual reversal (compare with fig. 37). It will be seen that in the second, response was feebler,

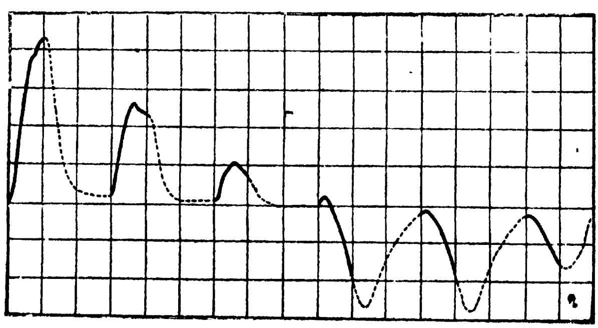


Fig. 41. Fatigue and reversal in AgBr cell.

and a tendency towards reversal had already taken place after an exposure of about 9 seconds. In the third, the response is feebler still. In the fourth, the normal response lasting for 3 seconds, is extremely weak; there is then a reversal of response which is fairly strong. On the stoppage of light the reversed effect persists for some time. After the fourth, the responses become reversed.

It will thus be seen that both electric radiation and light produce similar conductivity and electromotive variations. Two opposite effects are observed in both. The response curves are similar in the two cases. Under the action of continued radiation both exhibit a limiting effect. Under too long continued action, both exhibit a tendency towards or an actual reversal.

(*Proc. Roy. Soc. June* 1901.)

XV

ON THE SIMILARITIES BETWEEN RADIATION AND MECHANICAL STRAINS

In the previous paper various effects have been described caused by visible and electric radiation. Considerations were adduced which tended to show that these effects were due to molecular strain induced in the substance by the action of radiation. The whole history of the change produced by radiation, both the direct and after-effects, were graphically recorded in the various curves. The strain effect produced in a substance was shown to be attended with conductivity or electromotive variation. We shall next inquire whether strain, which is undoubtedly produced by mechanical means, gives rise to response by conductivity and electromotive variations.

As regards the conductivity variation due to mechanical strain, it is well known that in the construction of standard resistance coils, winding the wire on a spool causes a distinct variation of resistance, and that this strain effect can only be removed by annealing. The difference between the resistance of a substance when strained and after it is annealed is sometimes very considerable.

The effect of electric radiation in changing the conductivity of a mass of discontinuous particles is very great. It is to be borne in mind that the effect of electric radiation is only skin-deep. As the action is one of surface, the larger the surface the greater is the effect produced. As already stated, the effective surface accessible to radiation in loose particles is very much enlarged. Moreover, the resistance offered to the particles is not due to the individual solid lumps, but to the resistance of *surface* layer. It is precisely the surface layers that are affected by radiation, and hence the marked variation of resistance.

When the particles become continuous, the radiation can only affect the extremely thin layer of molecules on the surface, the mass in the interior being shielded by the outer conducting sheet; the molecular changes produced on the surface layer do not affect to any appreciable extent the conductivity of the mass.

For detection of strain effect in continuous solids the method of electromotive variation is the more suitable. It has been shown that light causes a P. D. between the acted and unacted plates. I shall next deal with the question whether mechanical stimulation gives rise to an electromotive variation between the acted and unacted plates.

1. *The Strain Cell*

For the purpose of the experiment, I made a voltaic element composed of two pieces WW′, taken from the same metal wire. These are fixed parallel to each other in an L-shaped piece of ebonite (fig. 42). The wires at their lower ends are fixed to the ebonite piece by means of ebonite screws SS′. The upper ends are fixed to metallic rods EE′ (which also serve as the electrodes), kept moderately stretched by springs CC′. The two electrodes lead to a sensitive dead-beat galvanometer of D'Arsonval type. A long handle, A, provided with a pointer, could be attached either to E or E′, and by its means either of the wires could be twisted. The angle of torsion is measured with the help of a graduated circle, not shown in the figure.

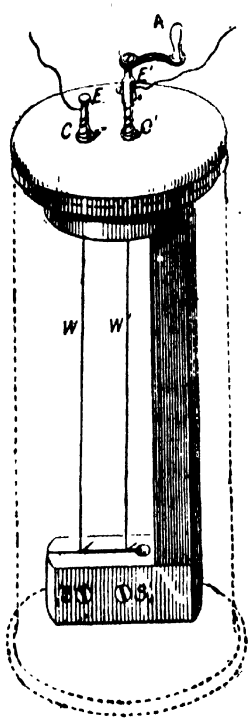


Fig. 42. The Strain Cell.

If a cell be made of two clean wires cut from the same piece, with water as the electrolyte there should theoretically be no P. D. between the two. But in practice a small P. D. exists between the wires, owing to slight difference in their molecular condition.

This initial difference can, however, be annulled by appropriate means, for example by subjecting them to mechanical vibration for a short time. After these precautions are taken, results are obtained which are extraordinarily consistent.

Now if one of the two wires be continuously twisted, an increasing P. D. is induced during torsion between the acted and the unacted wires. This may be measured by the deflection of the sensitive galvanometer. A curve of response could thus be obtained with electromotive force, measured by the galvanometer deflection, as ordinate, and the time during which disturbance is kept up as abscissa. Such curves were directly obtained by the recording apparatus described in my previous paper. The wire was twisted at a uniform rate. The successive dots represent the completion of 360°. To keep the deflection within the scale, a megohm was interposed in the circuit. The resistance of the cell was about 5000 ohms. The absolute values of electromotive force corresponding to the galvanometer deflections were subsequently obtained by noting the effect of a known electromotive force.

2. *Effect of Torsional Disturbance*

Most of the metals—exceptions presently to be described—become negative during molecular disturbance caused by torsion, *i.e.*, the current through the *liquid* is from the acted to the unacted wire. As there is a considerable vagueness in the terms *positive* and *negative*, which has led to much confusion, I would name the acted wire as becoming *zincoid* or Z, when under an external disturbance the current flows *through the electrolyte from the acted to the unacted wire.* Again, in certain cases the reverse is true; the current flows from the unacted to the acted wire; the acted wire will in that case be designated as *cuproid* or C.

The induced electromotive variation is not due to twist as such, but to molecular disturbance induced during increasing twist. For if the wire be held stationary in the twisted position, the molecular disturbance with the attendant electromotive variation will gradually disappear (fig. 43). Other facts will be brought forward to show that the effect is due to the molecular disturbance.

The wires used in the following experiments were from commercial specimens. The length was in every case about 9 cm., but the diameters were not the same.

The responses under electric radiation, and under the stimulus of mechanical vibration will presently be shown to exhibit remarkable similarities. Still more extraordinary are the similarities, that exist even in abnormalities, several instances of which will be given later; of these I shall mention here only one. It

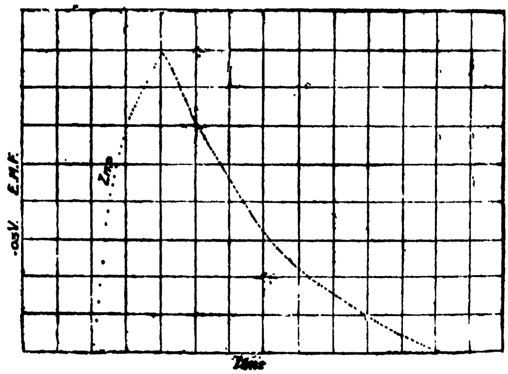


Fig. 43. E. M. variation due to torsion of zinc wire. Successive dots in the ascending portion of the curve represent effect of rotation through 360°. The descending curve represents recovery.

was shown in experiments with electric radiation that substances sometimes fall into a sluggish molecular condition, when the responses almost disappear. Strong stimulation (induction shocks, etc.) or annealing is then found to restore the sensitiveness. The same peculiarity is observed in the strain-cell. Lead, for example, specially on cold days, is apt to fall into a sluggish condition, when it becomes almost irresponsive. But it regains its sensitiveness after intense vibration or after annealing.

All metals (including the noble metal Pt) when molecularly disturbed exhibit electromotive effect. The intensity of electromotive variation depends on the nature and physical condition of the substance. The intensity of effect does not, however, depend on the chemical activity of the substance; for the electromotive variation in the relatively inactive tin is greater than that of zinc. The electrolyte used in the following experiments is common tap-water, but similar effects are also obtained with distilled water.

3. *Self-recovery*

It was said that the acted wire, usually speaking, becomes zincoid. This is not universally the case, for there are substances which become cuproid under mechanical stimulation. I have previously said that electric radiation produces opposite effects on different substances; silver is often found to show an effect (increase of resistance) opposite to that of generality of metals. It is very curious that silver is also often found to exhibit an opposite electromotive effect under mechanical stimulation, that is to say, the acted wire becomes C.

As long as the wire is not overstrained there is always a recovery. Observe the character of recovery in the curve for Zn when the twisting was stopped. It will be noticed that the recovery is very rapid at first, but slow in the later part, and that the recovery is complete.

4. *Irreversible Molecular Effect of Twist*

In the case of electric radiation or light, the impulses are of a vibrational nature, unlike the uni-directioned mechanical twist used in the above experiments. To make the two sets of phenomena comparable, we should have the mechanical disturbance of a vibrational nature also. I therefore next tried to see what the effect would be by reversing the direction of the twist, and found that the induced electromotive force is independent of the direction of twist, that is to say the electromotive variation is the same, whether the torsion is right-handed or left-handed.

I next tried the effect of a complete torsional vibration. I twisted the wire suddenly through +90°, then back to zero, then to—90°, and again back to zero, the complete vibration being executed in half a second. It will be seen that under these conditions we have a mere vibration and no resultant twist. This gives rise to an electromotive variation, the magnitude of which simply depended, as will be shown later, on the amplitude of vibration. It did not matter in the least whether the vibration commenced with a right- or left-handed twist.

It may be stated here that similar electromotive variation is obtained by molecular disturbance produced by a mechanical tap.

I shall now describe the effect of mechanical stimulus of varying intensities and durations. The intensity may be varied by varying the amplitude of vibration. We shall also study the effect of a single stimulus, or the summated effect of rapidly succeeding stimuli.

A set of experiments on the effect of mechanical stimulus may thus be carried out parallel to those on the effect of radiation stimulus. It would then be instructive to compare the response-curves of mechanical with those of radiation stimulus.

5. *Effect of a Single Stimulus*

For studying the effect of mechanical stimulus, a voltaic element made of " tin " wire* is very suitable. Normal responses are easily obtained after annealing.

* By tin wire is meant what is sold as such, and used as electric fuse. It is a pliable alloy of tin and lead.

As has been said before, any other metal may be used; I have, in fact, obtained as good results with platinum. But the advantage of tin is that the electromotive variation is comparatively strong; under favourable conditions this may be as high as 0·4 volt; another advantage is that it shows very little fatigue. On freshly making the cell, signs may be exhibited of abnormal irritability; this is due to the fact that a stable molecular condition has not yet been reached; but a more settled state soon supervenes, and after that successive responses are obtained which are extraordinarily regular and consistent amongst themselves.

That the response is due to molecular disturbance in the acted wire may be shown by the following experiment. The wire is clamped below; when the wire is subjected to torsional vibration, there is produced a strong molecular disturbance with the attendant electromotive variation. The wire is next released from the clamp and vibration imparted as before; there is now no electromotive response.

In fig. 44 is given a series of curves for different " intensities " of vibration. For want of space I have given a few only of each series. As a matter of fact, the succeeding series would have been mere repetitions of those which preceded. I have taken as many as 500 successive records, and each record is a mere duplicate of the rest. The substance does not exhibit any appreciable fatigue, especially if a period of rest be allowed for complete recovery. It will be seen that the rise is quick, whereas the fall is comparatively slow, specially in the later part.

With strain cells, there is no permanent change; the stimulated wire returns exactly to its original condition on the cessation of stimulus. In the border region between physics and chemistry no sharp line of demarcation can be drawn. In the case of tin cell the two wires are originally alike; under mechanical vibration a difference of potential is induced between the strained and unstrained wires. The induced electromotive variation disappears when the acted wire recovers

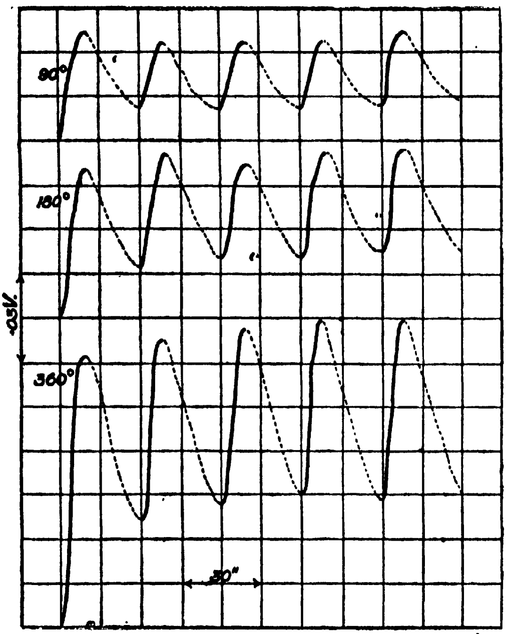


Fig. 44. E. M. variation due to a single vibration through 90°, 180°, and 360° in a Tin cell. Period of vibration 0·5". Thick lines represent effect of stimulus, dotted lines represent the recovery.

from stimulation. We may describe the same fact in chemical language by saying that owing to molecular strain the stimulated wire becomes chemically more active (zinc-like), and that the wire recovers its original condition on the cessation of stimulus.

6. *Increased Effect with Increasing Intensity of Vibration*

In fig. 44 are given the curves of response for single vibration, of amplitudes of 90°, 180° and 360°, the period lasting for 0·5 second. It will be noticed that the intensity of response increases with the energy of vibration.

7. *Effect of Summation of Stimuli*

In the case of effect of rapidly succeeding flashes of electric radiation on Ag′, it was shown (see fig. 36*d*) that the partial effects became fused together and that there was a limiting effect, kept balanced by the force of restitution. With rapidly succeeding mechanical stimuli, we again obtain precisely similar results. Fig. 45 (*a*, *b*) shows the effect of continuous vibration on tin cell, with different intensities of vibration, the vibration-frequency being twice in a second. The curve gradually rises and attains a maximum, at which position it is held almost rigid as long as the vibration is kept up. But on the stoppage of stimulation there is an immediate recovery, and if sufficient time be allowed the recovery is complete, as seen in the last curve of the series. The disturbance was kept up for 1 minute, and the period of recovery allowed was also 1 minute. In this way I obtained a long-continued series of similar responses, there being little fatigue; this is the case when a period of repose intervenes. But if the vibration is kept up without intermission, signs of fatigue begin to appear and the curve tends to fall. In some metals there may even be a reversal. Observe the flat top of the curve similar to that of Ag′ under electric stimulus mentioned above. Also the effects of different intensities of vibration, as shown in figure 45, (*a*) and (*b*).

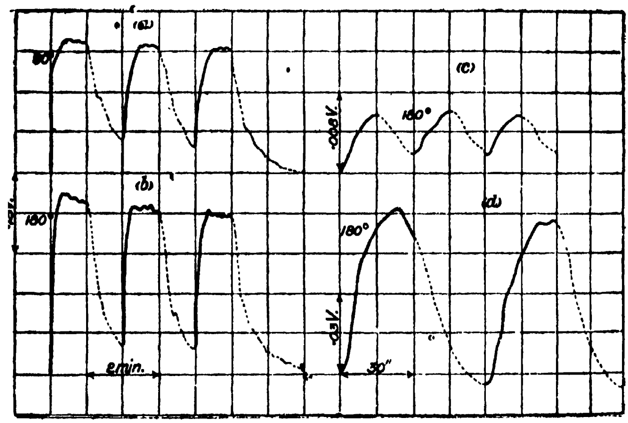


Fig. 45. Effect of continuous vibration. (*a*) and (*b*) show effects on a Tin cell. In (*c*) the effect on the particular Silver cell; the sign of E. M. variation is opposite to that of Tin cell. (*d*) shows the effect on a Nickel cell.

In (*d*) is shown the effect of vibration on Ni. After reaching the maximum there is a tendency towards reversal. Ni also shows greater signs of fatigue.

In (*c*), fig. 45, is shown the interesting curve for a given piece of Ag. The effect is very much feebler, and curiously enough it gave response of an opposite sign, the vibrated wire becoming cuproid. It was said that silver occupied a peculiar position as regards response to electric radiation, sometimes responding in one, and again in an opposite manner, probably owing to its readiness to pass from one molecular condition to another, under slightly different external conditions. With mechanical vibration, too, I find silver exhibiting positive or negative responses, the acted wire becoming on different occasions either Z or C.

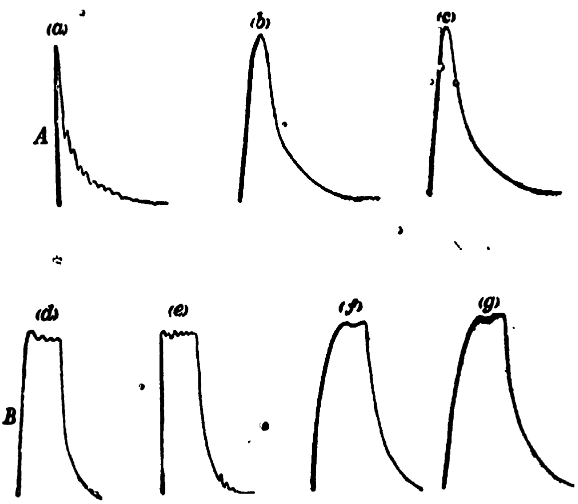


Fig. 46.

A. Effect of stimulus of short duration.
(a) Effect of electric radiation on Ag′ (conductivity variation).
(b) „ light on AgBr (E. M. variation).
(c) „ mechanical vibration on Tin (E. M. variation).

B. Effect of continued action of stimulus.
(d) Effect of continued action of electric radiation on Ag′ (conductivity variation).
(e) „ „ „ mechanical variation on Tin (E. M. variation).
(f) „ „ „ light on AgBr (E. M. variation).
(g) „ „ „ mechanical vibration on Nickel (E. M. variation).

8. *Reversal Effects*

Reversed Effect due to Sub-minimal Stimulus.—Just like the negative effect (*i.e.*, opposite to the normal) often exhibited under electric radiation when the stimulus is below the critical intensity, so also feeble mechanical stimulus often produces an effect opposite to the normal. Thus with strain cell made of lead, I found that whereas the acted wire became cuproid with an amplitude of vibration of 4°, the same wire when vibrated through 45° became zincoid. Thus in a Pb cell (50,000 ohms in circuit):

Amplitude of vibration.	Deflection.	Result.
4°	5 divisions to right.	Acted wire C.
45°	70 „ left.	„ Z.

The opposite effect under sub-minimal stimulus was too frequent to be accidental, but it did not occur invariably. On the occasions when it occurred, this negative effect disappeared after continued vibration. Thus on taking a record of effect of continued vibration, there is produced a negative twitch, which is converted later into a positive deflection, just as in the curves of effect of light (see below fig. 48).

Reversal produced by Continued Stimulation.—After the maximum effect the attainment of the further continuation of vibration tends to produce a reversal. This is specially the case with nickel in which the curve of response becomes completely reversed.

I have described the various molecular effects produced by mechanical stimulus under varying conditions, and shown how very similar they are even in details to the effects produced by electric radiation and light. How striking these similarities are will be seen from the following tabular statement and comparison of different curves.

9. *Response common to Electric Radiation, Light, and Mechanical Vibration*

1. The molecular effect produced may be detected either by conductivity or electromotive variation methods.

2. Substances when not overstrained exhibit recovery; the recovery is, however, delayed when there is overstrain.

3. Response is modified by previous history, and the influence of the surrounding conditions. Slight rise of temperature and annealing are generally favourable to increased sensitiveness and quick recovery.

4. Under the action of electric radiation, light, and mechanical vibration, two opposite effects are exhibited; by the conductivity variation method this is seen in the diminution or increase of resistance; a positive or negative variation is obtained by the method of electromotive variation.

5. In the curve of response, in all the above cases, the ascending portion is abrupt, whereas the fall during recovery is at first rapid, then comparatively slow, the curve of recovery being thus convex to the abscissa.

6. Under rapidly succeeding stimuli, there is a fusion of individual effects; the curve rises to a maximum, when the force of restitution is kept balanced by the force of molecular distortion.

7. Sub-minimal stimulus often produces a response of opposite sign to that of normal. Too long-continued stimulation produces, or tends to produce, a reversal.

8. Under certain molecular modifications, the response is of opposite sign to that of the normal. Continued stimulation converts the abnormal into normal. The response curve may thus exhibit, at the beginning, a negative twitch followed by the normal positive.

A number of curves selected from experiments already described, are given (see fig. 46) to illustrate graphically the remarkable similarities of response under diverse modes of stimulation.

10. *Effect of Stimulation by Light balanced by Mechanical Stimulation*

I have hitherto spoken of the similarities of the radiation and mechanical strains, but have not yet said anything about their mutual relation.

It is known that in cases where electric radiation produces an increase of conductivity, mechanical vibration produces an opposite effect, *i.e.*, an increase of resistance. It thus appeared that two opposite molecular effects were produced by the two different modes of stimulation.

In verification of this I investigated the effects of light and mechanical vibration in inducing electromotive variation in a strain cell. For this purpose I took a tin cell, and subjected one of the wires to the action of light and mechanical vibration alternately. The upper curve of fig. 47 shows the effect of light of

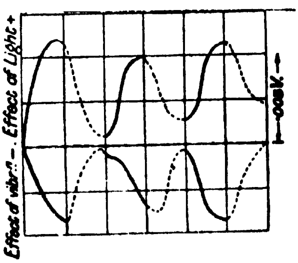


Fig. 47. Effect of light and torsional vibration on a Tin cell. Light makes the acted wire cuproid, mechanical vibration makes it zincoid.

a given intensity. It will be noticed that light makes the acted wire cuproid. But the action of mechanical vibration (see lower curve in same figure) makes the acted wire zincoid, and after several trials I found that a vibration with an amplitude of 3° produced a series of curves similar, but of opposite sign, to those produced by light. Mechanical vibration thus produced a molecular effect opposite to that of light.

I next allowed both the stimuli to act simultaneously on one of the wires; the action of light was then found to be exactly balanced by the action of mechanical vibration, an increase or diminution of either at once upsetting the balance.

The molecular effect of mechanical vibration thus appears, at least in the case of tin, to be opposite to that produced by light. This may be the case in general; the exception might be when one of the two stimuli is normal and the other sub-minimal.

XVI

ON THE STRAIN THEORY OF PHOTOGRAPHIC ACTION

The uncertainty in regard to satisfactory explanation of photographic action is due to the experimental difficulties in studying the problem. As for instance :—

(1) There is reason to believe that every substance is molecularly affected by radiation, but detection of the induced change is rendered impossible by the imperfection of methods hitherto available, and also by the subsequent self-recovery of the substance in darkness. The effects can be detected in a few cases only when the changes produced happen to be visible, or become visible on development.

(2) As regards direct chemical tests, taking for example, the case of AgCl, the quantity of radiation product is exceedingly small; this occurs in the presence of a very large amount of unchanged chloride and the isolation of the minute traces of changed product is extremely difficult. Various secondary reactions, moreover, complicate the phenomenon.

To arrive at a correct idea of the changes produced, it is necessary to measure the minute effects produced by radiation on the extremely thin layer—perhaps only a few molecules deep—of the sensitive substance. In order to ascertain this, it is desirable to begin with the study of some elementary substance in which its effects are attended with few secondary complications. And, lastly, it is necessary to have some means of studying all the stages of change in a continuous manner, so that the important preliminary phase of "molecular negotiation" may not be missed. I have in my two previous papers shown how the above ideal requirements may be realised by taking advantage of the conductivity or electromotive variation methods which not only enable the detection of extremely minute molecular changes produced by radiation, but also to follow the changes moment after moment in a continuous manner.

I have described in the two previous papers the various molecular effects induced by light, electric radiation, and mechanical stimulation, under diverse conditions. The consideration of these will give a clear insight into various obscure phenomena connected with photographic action, among which may be mentioned the following :—

1. Photo-chemical induction.
2. Relapse of invisible image.
3. Recurrent reversals.
4. The development of pressure marks.

1. "*Chemical*" *and* "*Physical*" *Theories of Photographic Action*

It is an arbitrary distinction to call a phenomenon either physical or chemical when it happens to be on the common border region. I have shown that when a substance is molecularly strained by light, its chemical activity is modified in consequence of the physical strain. The acted and the unacted portions will therefore be unequally attacked by a developer. In the case of a compound, the strain produced by light may cause a modification which renders it susceptible to decomposition by the action of a reducing agent. The observed evolution of chlorine when moist AgCl is exposed to the long-continued action of intense light is often adduced in support of the chemical nature of photographic action. This extreme case of dissociation cannot, however, be regarded as representative of the action of light in the formation of latent images. In ordinary photographic action we have merely the effect of a moderate stress producing the corresponding strain (with concomitant variation of chemical activity), and not the disruptive effect of a breaking stress.

With reference to photographic action, various facts are known which cannot be satisfactorily explained by purely chemical considerations. In connection with this the following experiment of Professor Dewar is suggestive. It is found that at the low temperature of —180° C., there is a cessation of all chemical action. Even such an extremely active substance as K does not show any action when immersed in liquid oxygen.* Now at these extremely low temperatures, where the action of such an active substance as K is suspended, an Eastman film was still found fairly sensitive to photographic action.

In the above case, it is difficult to see how light could have produced any chemical action upon the relatively inactive silver salt. It is more likely that the effect produced was of the nature of some physical strain. That light does produce molecular strain even at such low temperatures—a strain which may remain latent—is shown from Professor Dewar's experiments on phosphorescence. Ammon. Pt. Cyanide cooled to

* Dewar. Friday Evening Discourse at Royal Institution. June 26, 1891

—180° C. in liquid air absorbs light, but emits feeble radiation. But as the temperature is raised the stored-up light is emitted with very great intensity.

I now proceed to consider the photographic interpretations of the various molecular response curves taken under the action of radiation, as detailed in my previous papers.

2. *Substances may be Sensitive and yet give no Photographic Image*

The photographic effect on a sensitive plate is usually demonstrated by appropriate development, long after exposure. The after-effect of light on the sensitive substance may be fugitive or persistent. There are numerous gradations of this persistency of after-effect.

In order that the effect of light may be " developed," it is therefore necessary that the portions corresponding to the image should not in the meantime have recovered from the strain induced by radiation; for otherwise there would be nothing to distinguish the light-impressed portions from others not affected by light.

Though almost all substances are molecularly affected by radiation, yet there is a great difference in the permanence of after-effects. The recovery, as has been mentioned before, is very quick in some cases, whereas in others it may be protracted.

It is obvious that any method which attempts to develop the after-effect a long time after exposure will not be successful in cases where there is a quick self-recovery. It will only be successful where the strain effect is more or less persistent.

It is thus seen that it is quite possible for a substance to be sensitive to radiation, and yet seem to show no effect capable of photographic development, owing to rapid self-recovery.

3. *Relapse of the Invisible Image*

The above considerations afford a simple explanation of the very obscure phenomenon of the relapse of the invisible image. Recovery is merely a question of time. With certain substances it is immediate, with others it takes a longer time, as in a daguerreotype, where the latent image disappears in the course of several hours. In ordinary photographic plates the recovery may not take place for several years. We have seen how the strain effect of electric radiation was transient in some cases, whereas it was more persistent in others.

It is evident that in order to make the after-effect more or less permanent, and thus render it developable, self-recovery should be retarded. There are two ways in which the after-effect may be rendered comparatively permanent: (1) Even a highly elastic substance may be rendered more or less permanently distorted by straining it beyond the limit of elastic recovery; or (2) the presence of a retarding substance may prevent the self-recovery of the sensitive material. One of the chief functions of the so-called sensitisers may pobably be in preventing self-recovery and rendering the after-effect permanent.

4. *Permanence of the After-effect by Overstrain*

Thus in many cases where images cannot be secured with ordinary exposure, they can be obtained with excessive strain caused by prolonged exposure. Thus Moser obtained an invisible image on a clean silver plate by exposing it to the sun for 2 hours or more. The invisible image was afterwards fixed by development with mercury vapour. A similar result was obtained with copper.

Major-General Waterhouse describes a very interesting series of investigations* in which by prolonging the exposure, printing-out impressions were obtained on silver. These could be developed not only by mercury or water vapour, but also by ferrous sulphate or pyrogallic developers. Images were also obtained on lead and gold.

These results derive an additional interest from the fact that most of the phenomena that occur by the exposure of ordinary photographic plates containing haloid compounds of silver can also be observed upon a silver plate exposed to light. In my experiments on molecular effects produced by electric waves, I found *all* metals sensitive to electric radiation, owing to the extremely sensitive method of conductivity variation. The molecular effects of visible radiation on various substances are also exhibited by the method of electromotive variation. In the experiments of Waterhouse, a considerable number of metals were found to be sensitive to visible radiation, the effect being rendered more or less permanent by overstrain.

5. *Electromotive Variation Curve due to Light*

I give below one out of several similar curves, showing the effect of continuous light on one of the two plates of a photo-electric cell of AgBr (fig. 48). In this curve several distinct stages are noticeable.

* Waterhouse, 'Proc. Roy. Soc.' April, 1900.

(1) A short latent period, where there is apparently little or no action or even a transitory negative action. The curve given had to be contracted to put in all the different phases, and the peculiarities of the first part cannot therefore be very well shown.

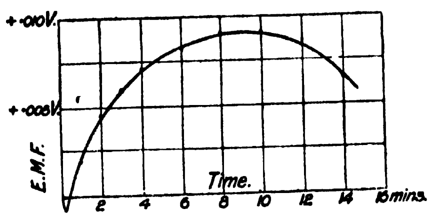


Fig. 48. E. M. variation curve for AgBr cell, under the continued action of light. Note the preliminary negative twitch.

I have previously remarked that in general the molecular strain curve is in the first part slightly convex, then straight, and in the last part concave; this is true not only under the action of stimulus of light, but also of mechanical vibration.

(2) In the second stage, the curve of response rises almost in a straight line, this being the phase of increasing action.

(3) The curve then reaches the maximum and becomes horizontal; after which it begins to fall thus exhibiting a reversal.

(4) During prolonged exposure the response-curve sometimes exhibits recurrent reversals.

The similarities of the molecular effects produced by light and by mechanical vibration have already been explained. The recurrent reversals are also occasionally obtained under mechanical vibration, as in the following electromotive variation curve for nickel (fig. 49), which was subjected for a long time to continuous mechanical vibration.

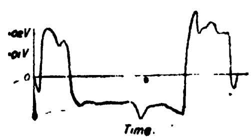


Fig. 49. Recurrent reversals obtained with a Ni-cell under continued vibration.

6. *Photo-chemical Induction*

The first part of the curve, or the latent period, is very suggestive as regards the obscure phenomenon of photo-electric induction. Thus " Quantitative measurements have shown that the action of light is not instantaneous. On the contrary, it gradually develops, and requires a considerable time before it attains its full strength. When a mixture of chlorine and hydrogen, which has been kept in the dark, is exposed to the light, there is either no hydrochloric acid or only a very small quantity formed in the first moment ; but the rate of formation increases so that the quantity formed in a given time, *e.g.*, a minute, continues to increase until it attains a maximum value. Bunsen terms the gradual increase in the action *induction*. If the gaseous mixture has been once exposed to the light, it will retain in the dark, for about half an hour, its capacity for forming HCl in the light. If the gas has remained in the dark for a short period and is again brought into the light, it requires a very short period of induction ; but the period of induction will be lengthened by keeping the mixture in the dark for a long time. [This is evidently due to self-recovery. J. C. B.]. Exposure to the light renders the gaseous mixture capable of entering into combination, but it does not bring about combination itself."*

The latent period of the curve, due to molecular inertia, would thus appear to offer an explanation of induction. In connection with this it is interesting to note the well-known fact that a very slight preliminary exposure of the photographic plates considerably enhances their sensitiveness.

It would also appear from the inspection of the curve, that the general law of photo-chemical action, which regards the total action as proportional to the product of the light intensity multiplied by the time of exposure, is subject to several modifying conditions. During the latent period, this cannot hold good in the first part, nor can it be true after the maximum is reached. It can hold good only in the second stage where the action proceeds uniformly.

7. *The Effect of Intermittence in Modifying the Law of Photo-chemical Action*

But even after the substance has arrived at the second stage of uniform action, there may still be deviation from the above law. If in one case light be intermittent, and in the other continuous, the effects may be quite different, though the total durations be equal. For in the former case, during the continuation of light we may have distortion or molecular swing proceeding in a given direction, but on the stoppage of light, the swing stops too, sooner or later (sooner if the distortion has been considerable, when the force of restitution becomes great), and owing to self-recovery may even become reversed. After an interval, when the light is again

* Meyer, 'Modern Theories of Chemistry,' p. 507.

allowed to act, it has not only to overcome the molecular inertia, but may have in certain cases to reverse the negative swing. In the case of continuous radiation, on the other hand, the molecular action proceeds without hindrance.

This is very well seen in the curve given below, which shows the difference in the extent of molecular effects produced in an AgBr cell by interrupted and continuous illuminations of the same total duration (fig. 50). Though light acted for the same length of time in both cases, yet in that of interrupted illumination the molecular effect as measured by the galvanometer deflection was only seven divisions, whereas with continuous illumination the deflection was 11·5, or one and a-half times as great.

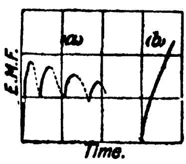


Fig. 50. Effect of (*a*) intermittent and (*b*) continuous illumination. In (*a*) there are four interrupted illuminations of 15″ each, the total duration being 1′. In (*b*) there was continuous illumination for 1′.

It is thus seen that owing to self-recovery, the effect of light with intermittent illumination is less. It is also evident that the greater the period allowed for self-recovery (during the interval of darkness) the less will be the resultant effect. In connection with this, the experiments of Abney are very interesting. In experimenting on the difference between the effects on photographic emulsion of a continuous exposure and a series of intermittent illuminations, he finds that in the latter case the effect produced was always less, and that the longer the interval between the exposures, the smaller was the effect.

8. *Photographic Effect Modified by Time-rate*

It will thus be seen that the photographic effect is not solely governed by the total amount of radiation, but by the time-rate also. The influence of this factor appears to be exhibited in the following cases. Cases (2) and (3) derive an additional interest from the fact that the effects are probably due not to absorption of radiation, as is usually the case in photography, but to the emission of radiation.

(1) In photographs of lightning, the line of discharge often comes out dark (the so-called dark lightning). It has been shown that reversals are produced by intense radiation ; we may thus have reversals of the first, second, and succeeding higher orders. Now it is possible that the reversal, or the dark-lightning effect, may be obtained, not only by a subsequent diffuse illumination (Clayden effect), but also by the action of lightning itself, provided that the intensity of illumination is sufficiently great and sudden to produce the reversal. The luminous intensity of lightning discharge is incomparably higher than any that can be produced by a spark from an electric machine. Mr. R. W. Wood* obtained reversal with a single spark, when the photographic lens was

* 'Nature', November 30, 1899.

wide open, but there was no reversal with four sparks, the light aperture being reduced to one-fourth. The quantity of light was the same in the two cases, but the time-rate of illumination was different. This curious result would no longer appear anomalous, if we bear in mind the experiment in which the influence of time-rate was shown.

(2) In trying to obtain photographs by heat radiation on sensitised papers coated with a mixture of silver and mercury iodides, the following curious effect was observed. The sensitised paper was exposed to heat radiation and became uniformly reddish in colour. A mask with cut-out letters was now put on it, and the sensitised paper was allowed to cool. The rate of cooling was very rapid at the places exposed by the cut-out letters, whereas at the covered portions the rate of cooling was very much less. After a long time when the sensitive paper had cooled down to a uniform temperature, prints were still visible, the effect being evidently due to the different rates of emission of radiation in the screened and unscreened parts.

(3) Major-General Waterhouse mentions an anomalous case which seems to be explicable from considerations given above. He took a polished silvered glass plate, and put it into a printing frame with a cut-out paper mask and mica screen in which were cut-out initials, just as if it were going to be exposed to the sun; but instead of exposure

to light the plate was gently warmed for about 5 minutes over a spirit lamp, and then developed with mercury. The cut-out initials came out distinctly in dark lines. It would thus appear that since the plate was uniformly warmed, the difference between the screened and unscreened portions could only be in the different rates of emission.

9. *Phenomenon of Recurrent Reversals*

The fourth stage in the curve for the action of light will be found specially interesting with reference to photographic reversals, which are found to be recurrent. Thus, starting with a neutral condition, we obtain the first negative with a moderate exposure; longer exposure will tend to reduce the intensity of the negative and give rise to a neutral condition. Further exposure gives rise to a *positive*, then a second neutral, and again a succeeding negative, and this may be repeated in recurrent series.

Such recurrent reversals are also exhibited (see fig. 49) by a substance under continuous mechanical vibration. In my paper on "Electric Touch" I have given similar instances of reversals produced by the action of long-continued electric radiation.

10. *Other Methods of obtaining Latent Image*

If molecular strain be the basis of all photographic phenomena, then it ought to be possible to obtain latent images by other methods of producing molecular strain.

An instance of this is seen in the development of mechanical pressure marks. Images produced by electric strain are observed in the "inductoscripts."

11. *Conclusion*

It is thus seen—

(1) That molecular strain is produced by the action of light.

(2) That as the physico-chemical properties of a substance are changed by strain, it is possible to develop the latent image through the difference in the following properties between the exposed and unexposed portions produced by light.

(*a*) Difference in adhesive power, *e.g.*, development of daguerreotype by mercury vapour, development by water vapour.

(*b*) Difference in chemical stability, *e.g.*, development by reducing agents.

(3) That molecular strain may not only be produced by visible or invisible radiation, but also by (*a*) electric induction, and (*b*) by mechanical distortion. Latent images produced by such means may be developed, *e.g.*, inductoscripts, and pressure marks.

(4) That nearly all substances are sensitive to radiation, but the effect cannot in all cases be rendered visible, (*a*) owing to want of suitable chemical developers, (*b*) owing to quick self-recovery. The molecular effect due to radiation can, however, be demonstrated by the conductivity or electromotive variation methods.

(5) That the latent period of overcoming inertia corresponds to the photographic induction period.

(6) That the relapse of image is due to self-recovery.

(7) That owing to the tendency towards self-recovery the radiation effect does not solely depend on the total quantity of light, but depends also on the time-rate of illumination. Hence the photographic effects of intermittent and continuous illuminations of equal total durations, are not the same.

(8) That the continuous action of radiation produces recurrent reversals.

(9) That the molecular effects produced by light and electric radiation are similar.

XVII

ON THE CHANGE OF CONDUCTIVITY OF METALLIC PARTICLES UNDER CYCLIC ELECTROMOTIVE VARIATION

A mass of conducting particles has its conductivity changed when subjected to rapid electric vibration, as for instance, when acted on by electric waves. I have, in previous papers, adduced reasons leading to the conclusion that electric radiation produces a molecular change, and that conductivity variation is the expression of the induced change. We know that the physical properties of a given substance depend on its molecular condition. Any molecular change that may be induced may therefore be expected to be attended by changes in the physical properties of the substance, electric conductivity being one of these. The wide difference in electric conductivity of the same substance under different molecular conditions is seen in the case of carbon, in its two allotropic forms of graphite and diamond. The effectiveness of radiation in producing allotropic changes is seen in the conversion of the yellow into the red variety of phosphorus under the action of light.

That the variation of conductivity induced by electric radiation is due to some atomic or molecular action is seen from the fact that it is dependent on the chemical nature and the molecular condition of the substance. Thus, under electric radiation, the positive class of substances, *e.g.*, Fe, Mg, etc., exhibit an increase of conductivity, whereas the negative class of substances, *e.g.*, K, Br, I, show a diminution. The effect of molecular conditions in determining the sign of response to electric radiation (*i.e.*, increase or diminution of conductivity) is exhibited by the two molecular varieties of silver, the response being positive in one case and negative in the other.

The conductivity variation is thus the expression of some molecular change. In many cases (potassium, Ag, brominated lead, etc.) we find that the change persists only during the action of radiation. On the cessation of the stimulus the substance at once shows elastic self-recovery. It would thus appear that the conductivity variation is due to molecular strain produced by radiation. This view is further supported by the fact that in working with self-recovering receivers of various types, both positive and negative, I have not only found that for each intensity of radiation there is a corresponding conductivity variation, but that under the continued action of radiation, the conductivity variation attains a maximum value, which remains constant, balanced by a force of restitution; when the radiation is stopped, the subtance is found to recover its original conductivity. With an increase of intensity of radiation, the corresponding conductivity variation also increases, and *vice versa*. I have, in a Paper "On the Continuity of Effect of Light and Electric Radiation on Matter" given an account of self-recovering receiver, of negative type, made of silver particles, in which the conductivity variation is almost exactly proportional to the intensity of radiation. Self-recovery, in general, is merely a question of time; with certain substances it takes place immediately, with others, after a short or after a comparatively long period. This view of conductivity variation, as the expression of some molecular change, will receive independent support from the experiments on a self-recovering receiver to be described later.

The conductivity changes take place not only under very rapid Hertzian oscillations, but also under much slower electromotive variations. Thus an electromotive variation, whether quick or slow, is the effective cause of induced change of conductivity. In substances which exhibit recovery from the action of radiation so protracted, as to appear practically non-recovering, the induced molecular change is attended by a more or less permanent variation of conductivity. Recovery in such cases can be hastened by molecular vibration, by mechanical taps, or by the application of gentle heat.

After a rapid cyclic variation of E. M. F. the substance is thus transformed from its primitive condition; in other words a more or less irreversible molecular change is induced at the end of the process as exhibited by a hysteresis of conductivity. If this view be correct, then we can study the molecular change step by step, by observing the conductivity variations undergone by the substance as it is carried through a complete cycle of electromotive variation. The rapidity of this process must be just sufficiently slow to allow the successive changes to be recorded. The suddenness of electric variation no doubt exerts an influence on the amount of change; but this is a question of degree only.

The investigation thus resolves itself into the determination of the variation of conductivity of the sensitive particles, as the mass is subjected (1) to a continuously increasing E. M. F. from zero to a maximum, and then (2) to a continuously diminishing E. M. F. from the maximum back to zero. The required information may be obtained by the interpretation of the characteristic curve, in which the abscissæ represent the impressed E. M. F., and the ordinates give the corresponding values of the current. A continuously increasing E. M. F. can be made to act on the sensitive substance, by the movement of a slider over a potentiometer wire, say, to the right. The scale readings of the potentiometer give the values of the E. M. F. The readings of the galvanometer in circuit give the corresponding values of the current; movement of the slider to the left produces a continuous diminution of E. M. F. The characteristic curve can thus be obtained from the observed values of E. M. F. and the corresponding currents.

This is a bare outline of the principle of the investigation described in this Paper. Various experimental modifications have to be introduced in order to overcome certain difficulties and render the method practical.

Before entering upon the subject of experimental arrangements, I may repeat what I pointed out in my paper on Electric Touch that in regard to their response to electric radiation, there are three types of substances, positive, negative and neutral, differentiated "by the characteristic curves of variation of current with E. M. F." The positive exhibits an increase of conductivity; the negative shows a diminution of conductivity; and the neutral does not exhibit any conductivity change. The first two of these classes again fall into two subdivisions, of substances which exhibit self-recovery and those which do not. The characteristic curves of the three classes of substances thus belong to three distinct types, so that it is possible to determine the class to which the sensitive substance belongs by its characteristic curve.

These curves also throw much light on the obscure subject of the action of radiation on various sensitive substances. In the present Paper I shall describe in some detail the reaction of the first class of substances. *i.e.*, those which show a diminution of resistance, and amongst these I shall take typical instances of non-recovering and self-recovering substances, and demonstrate the peculiarities of their cyclic characteristic curves. A brief reference will also be made of the characteristics of the second class which exhibit an increase of resistance.

Experimental Arrangements

The electric circuit consists of (1) the sensitive substance, (2) a sensitive dead-beat D'Arsonval galvanometer, and (3) a potentiometer arrangement for a gradual and continuous increase or diminution of E. M. F.

1. *The Sensitive Substance.*—Experiments were made with both single and multiple contacts. In the former case the pressure of contact was adjusted by means of a fine micrometer screw, or by means of springs. In some cases the contact ends were both rounded; in others, a pointed end pressed against a flat piece.

In the case of multiple contacts, a small quantity of metallic filings was put in a glass tube, and the fragments compressed between two electrodes, the pressure being regulated by a perfectly easy-running micrometer screw. The pressure was adjusted till a feeble initial current flowed through the circuit. The micrometer screw, together with the tube of filings, were appropriately fixed on a heavy base. This rested in turn on a steady pedestal, with one or two sets of pneumatic tyres interposed. Experiments were carried out with the sensitive substance in air, or immersed in kerosine.

2. *The Galvanometer* was appropriately shunted so as to give a deflection of one division of scale for a definite small fraction of an ampere. In some experiments, for example, one division of the scale was equal to 10^{-6} ampere. The calculation of resistance of the sensitive substance is very much facilitated if the scale values of the galvanometer and the potentiometer were suitably adjusted beforehand. The resistance of the shunted galvanometer and the potentiometer was practically negligible in comparison with the resistance of the sensitive substance, which usually varied from about 1,000 to 50,000 ohms.

3. *The Potentiometer* consisted of a thin nickeline wire of uniform section, 20in. in length. Each inch of the scale was further sub-divided into tenths. A storage cell with an interposed resistance was applied to the terminals of the potentiometer, and the resistance adjusted till the terminal E. M. F. attained a suitable value. This was found by the help of an auxiliary voltmeter applied to the terminals of the potentiometer.

The E. M. F. acting on the main circuit was derived from the potentiometer; one end of the circuit was connected with one terminal of the potentiometer and the other connected with a slider, the movement of which to the right or to the left increased or diminished the impressed E. M. F. The sliding contact was made by means of a bent flat metallic spring which uniformly pressed against the potentiometer wire. Care was taken to maintain a uniformly good electrical contact. Any sudden introduction of the E. M. F. was avoided with special care, as, owing to the self-induction of the circuit, an unknown induced E. M. F. might act on the sensitive substance. The slide-contact was therefore never broken; starting from zero of the scale (E. M. F.=0) the slider was moved at a uniform rate to the right, thus continuously increasing the E. M. F. without any sudden variation. Movement of the slider to the left produced a continuous diminution of E. M. F. The voltaic cell was never cut off from action till the slider returned to zero.

Method of Observation

One observer moved the slider at a uniform rate and called out the successive potentiometer readings; the corresponding deflections of the galvanometer were read off by the second observer, and a third took down in parallel columns the applied E. M. F. and the corresponding galvanometer readings. From these data the characteristic curves could be subsequently obtained. This method of work was, however, very tedious. It took a long time and the co-operation of three persons to complete one experiment, and the curves could only be obtained from a series of observations which were not absolutely continuous. I had, therefore, to devise a recording apparatus by which a continuous curve could be obtained in a simple and direct manner.

Recorder of Conductivity Variation

If a platform be fixed to the slider of the potentiometer, then the movement of the platform in one direction would continuously increase the E. M. F. acting on the circuit containing the sensitive substance (fig. 51). If the galvanometer spot of light is thrown down on the platform by a mirror, suitably inclined, and if

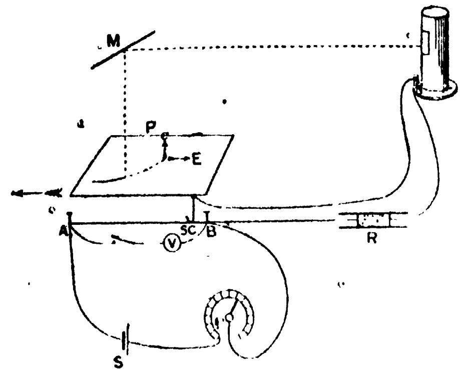


Fig. 51. Diagrammatic Representation of Conductivity Recorder.
P, Moving Platform. AB, Potentiometer. R, Sensitive Receiver. r, Rheostat
V, Voltmeter. SC, Sliding Contact. S, Secondary Cell. M, Mirror.

the movement of the spot of light, due to variation of current, takes place at right angles to the motion of platform, then a continuous curve would be traced on the platform, of which the abscissæ would represent the E. M. F. and the ordinates the currents. This curve could be fixed if we laid a sheet of photographic paper on the platform, or we might obtain it by the simpler expedient of following the track of the galvanometer spot with a pencil.

I used squared paper for recording the curves. It is divided into inches, and these further sub-divided into tenths. The potentiometer wire is 20in. long, and the length of the platform is the same. As the platform moves through its own length past a fixed index; the sliding contact moves through the whole length of the potentiometer. If the applied E. M. F. at the terminals A and B be, for example, 1 volt, each inch of paper along the platform would then represent $\frac{1}{20}$th or 0·05 volt, the smaller sub-division representing 0·005 volt. This or any other suitable terminal value of E. M. F. can be obtained with the help of the storage cell S, a rheostat r and an auxiliary voltmeter V, applied to the terminals A and B.

The galvanometer, as was said before, is also adjusted by means of a shunt, so that a deflection of one division is a convenient small fraction of an ampere. The absolute values of the E. M. F. and current being known, the resistance of the sensitive substance at any point of the curve can easily be determined.

In the completed apparatus the platform is mounted on small wheels and moves on rails with perfect smoothness. A string connected with one end of the platform is carried round a large winding wheel and a second string connected with the other end of the platform carries a counterpoise. When the wheel is turned at a uniform rate in one direction, the platform carrying the paper also moves at a uniform rate, at the same time producing a continuous increase of E. M. F. acting on the circuit. When the wheel is turned in the opposite direction, the counterpoise reverses the motion, and the impressed E. M. F. undergoes a continuous diminution. In this way it is possible to produce either an increase, or a decrease, or a rapid cyclic variation of E. M. F. I shall first describe in detail the rising part of the curve thus obtained, and then deal with peculiarities of complete curve when carried through a cycle.

Characteristic Curve of a Single Point Iron Receiver

In order to reduce the conditions of experiment to their simplest, I first studied the effect of E. M. variation on contact at a *single* point. The change induced was thus confined to the molecular layers at the point of contact. This consisted of a sharp point of iron, pressing against a convex iron surface, the pressure being capable of very delicate adjustment by means of a micrometer. Five different experiments were carried out with the same receiver.

The initial adjustments were made with an E. M. F. of 0·05 volt. The only difference made in the several experiments is as regards the initial current, caused by change in the pressure of contact.

In curve A (fig. 52) the initial current was the lowest value of the series. The pressure of contact was adjusted till the initial current at 0·05 volt was $2/10^5$ ampere. The E. M. F. was now continuously increased by the turning of the winding wheel, and the curve obtained in the manner previously described.

It will be seen that the curve is not straight, but concave to the axis representing the current. As the E. M. F. is increased, the current increases at a greater ratio. I may say here, in anticipation, that this appears to be a characteristic of the positive class of substances, *i.e.*, of those which, like iron, exhibit a diminution of resistance under electric radiation.

The resistance of the receiver is thus not constant, but undergoes a *continuous* decrease with increasing E. M. F. The conductivity is therefore increased with the rise of E. M. F. The curve becomes steeper as the E. M. F. is increased, the conductivity undergoing a rapid and continuous increase.

Hence conduction in such cases does not obey Ohm's law. The resistance is not independent of the E. M. F.

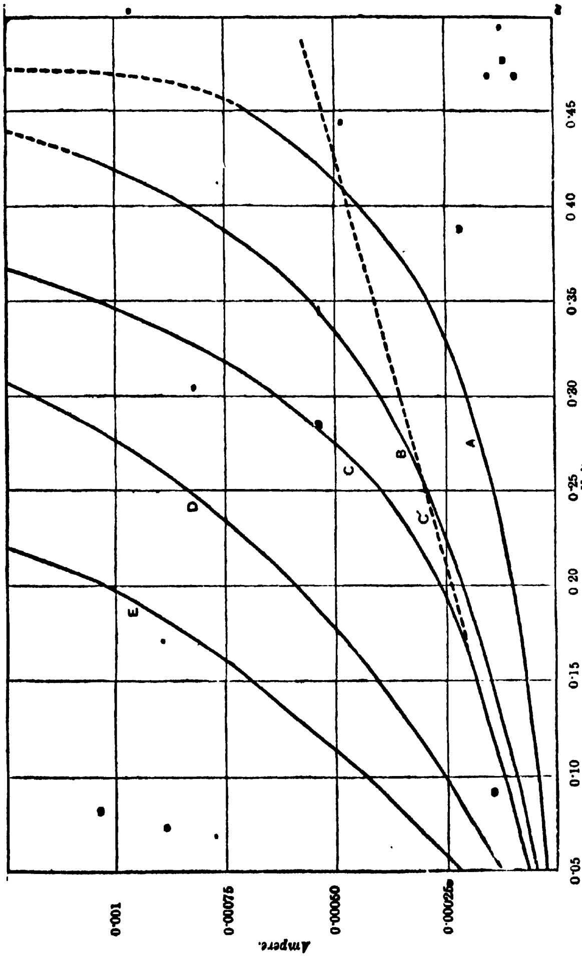


Fig. 52. Characteristic Curves of a Single Point Iron Receiver.
A, B, C, D, E are different curves for different initial currents. C′ is the curve for a constant resistance.

but varies with it. A remarkable analogy is here presented with the phenomenon of magnetic conduction. Just as the magnetic permeability of iron is not constant, but varies with the magnetic force acting on it, so the conductivity of metallic particles is not constant, but varies with the E. M. F. acting on them. The characteristic curves given above bear also a remarkable resemblance to the curves of magnetisation. Other parallelisms will be noted later. These similarities are probably due to the fact that in both cases we are dealing ultimately with phenomena of molecular deflection and rearrangement, taking place in one, under increasing magnetising force, and in the other, under increasing electromotive force.

As the absolute values of the current and the E. M. F. are known, it is easy to find the resistance of the receiver for any given E. M. F. The different values of the resistance can also be determined by the *method of substitution*. After the curve is drawn, leaving the paper still on the platform, a resistance box is substituted for the receiver, and the whole operation is repeated, with this difference, that now we have to change the resistance continuously in order to keep the galvanometer spot on the curve. The values of these resistances at definite points of the curve now correspond to the resistances of the receiver at those points. We can thus find the value of the resistance of the receiver at any point in the curve. This way of finding the resistance was used to supplement that of direct calculation $\left(R=\frac{E}{C}\right)$, from the known values of the E. M. F. and the corresponding current; the two results were found practically identical.

I give below a table showing the variation of resistance with E. M. F. for the curve A (fig. 52).

Table I.—Showing the Variation of Resistance with E. M. F.

E. M. F. (volt).	Current (in $1/10^6$ amps)	Resistance (ohms).
0·05	2·0	2,500
0·10	4·1	2,440
0·15	6·6	2,270
0·20	9·2	2,100
0·25	14·0	1,770
0·30	20·0	1,500
0·35	28·5	1,230
0·40	44·6	860
0·45	69·0	640

It will be seen from the above table that as the E. M. F. increased from 0·05 volt to 0·45 volt the resistance decreased continuously from 2,500 to 640 ohms, *i.e.*, about one-fourth its original value, and *this diminution of resistance or increase of conductivity is not abrupt, but continuous.*

In the lower portion of the curve, where the E. M. F. is low, the resistance is great and its variation small; but the curve soon becomes steep with the rise of the electromotive force. With a higher E. M. F. the change, to which the conductivity variation is due, proceeds very rapidly. This change is so great that at a certain critical value of E. M. F. it is almost abrupt. This is well seen in curve A, a little beyond 0·45 volt.

When the E. M. F. is adjusted to fall just short of the critical point, say, at 0·4 volt, then a slight increase of E. M. F., say +0·1 volt, will cause a very great variation of current; whereas if the E. M. F. had been so adjusted as to fall very much below the critical point, say, at 0·3 volt, an additional electromotive force of the same amount 0·1 volt, produces a relatively small variation of current. In the former case, conditions stood as it were on the brink of a precipice, and a slight additional impetus precipitated a fall. It will thus be seen that if the E. M. F. acting on the receiver be so adjusted as to be near the critical point, a slight electromotive variation will produce a great change, exhibited by a very considerable increase of conductivity. It is interesting to note in this connection that I found the sensitiveness of receivers to electric radiation could be greatly enhanced by raising the E. M. F. acting on the circuit to a point as high as they could bear, just short of electric instability.

Influence of Intensity of Initial Current in Modifying the Characteristic Curve

When at the beginning of an experiment the receiver is adjusted at a definite low E. M. F., say, 0·05 volt, we can have any initial current, according to the adjusted pressure of contact, the current increasing with increase of pressure. We may thus start with a large or a small initial current, the E. M. F. at starting being constant.

In the curve B (fig. 52) the initial current is a little more than double that for A. It will be seen that the curve has become distinctly steeper; the critical point is at the same time lowered, from 0·46 volt as in the last case, to 0·43 volt. The sudden bend in the curve is now less pronounced. In connection with the lowering of the critical point by pressure, it is also interesting to note that by increasing the pressure within certain limits, I succeeded in greatly enhancing the sensitiveness of the receiver to the action of electric radiation, In the curves C, D, and E the initial currents were increased with resulting increase of steepness of the curves.

In order to test further the accuracy of the adjustments, I have taken on the same chart, the curve for a constant resistance. In C, the resistance of the receiver at 0·15 volt was found to be 830 ohms. A resistance box having the above resistance was substituted for the receiver, and a curve traced in the usual manner. This curve C′ is seen to be a straight line.

I give below a table showing the results of four sets of experiments on the variation of the resistance *r* and of conductivity *c* of the receiver under increasing E. M. F.

Table II.—Showing the Diminution of Resistance of the Receiver, with increasing E. M. F.

E. in volt.	B		C		D		E	
	Current in 1/10⁵ amp.	Resist in ohms.	*c*	*r*	*c*	*r*	*c*	*r*
0·10	9	1,136	12	830	25	400	43	232
0·15	14·2	1,060	18	830	40	375	69	217
0·20	20·5	970	26	770	59	340	102	196
0·25	29·5	850	40	625	83	300	...	...
0·30	40	750	63·5	472	118	254	...	...
0·35	56	620	105	333	...	...	...	...
0·40	85	470	...	...	...	...	...	...

It will be seen that in all the above cases the resistance undergoes a continuous diminution with the increase of E. M. F., and that the diminution of resistance due to electromotive variation is not an abrupt, but essentially a continuous process.

Experiments with Receiver Immersed in Kerosine

In order to find out whether the exclusion of atmospheric action would change the general character of the result, I took observations with a single point iron receiver immersed in kerosine.

Table III.—Showing the Diminution of Resistance with Increasing E. M. F. in a Receiver immersed in Kerosine

E. in volt.	Current in $1/10^6$ amp.	Resistance in ohms.
0·05	15	3,333
0·10	35	2,857
0·15	56	2,678
0·20	78	2,564
0·25	124	2,016
0·30	182	1,648

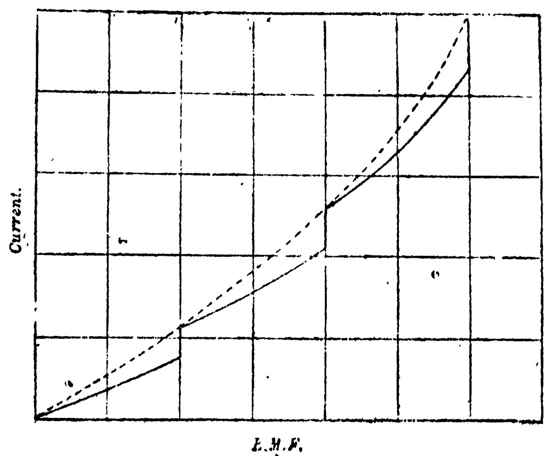


Fig. 53. Effect of Lag.

It will be observed that under the above condition also, there is a continuous diminution of resistance with an increase of E. M. F.

Time-lag

The changes which give rise to the conductivity variation take a short time for their completion. The curves were taken when the electromotive variation was produced at a moderate and uniform speed. But if the electromotive variation is produced quickly and step by step, each step being followed by a pause, then

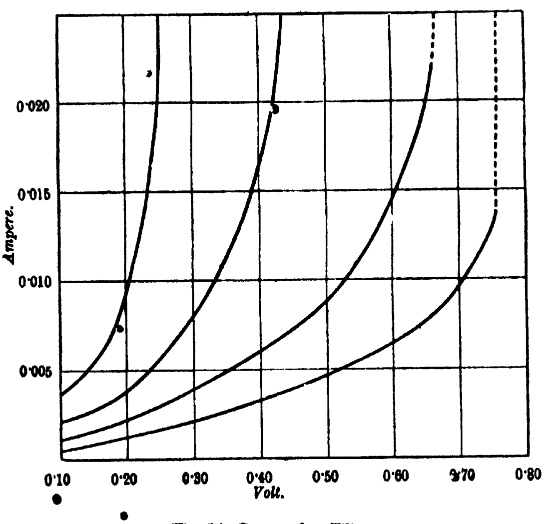


Fig. 54. Curves for Filings.

there is an immediate effect, followed by a permanent effect, the galvanometer deflection creeping up to this permanent value. This creeping effect becomes more marked with higher E. M. F. I give above a record where this effect is shown (fig. 53). The vertical portions of the curve represent the creeping effect during pause. The conductivity variation thus lags slightly behind the impressed electromotive variation. Certain effects due to this will be noticed later.

Characteristic Curves given by a Mass of Iron Filings

Owing to the multiplicity of contacts the conditions here are not so simple as in the case described above. It will, however, be seen from the curves given in figure 54, that the results are of the same general nature. The resistance undergoes diminution with increasing E. M. F. The curves are steeper with stronger initial currents. Greater intensity of initial current appears also to have the effect of lowering the critical point. I obtained similar results with Mg, and Ni.

It is difficult in one curve to represent adequately the variation of conductivity caused by small, moderate, and excessive increase of E. M. F. Broadly speaking, the curve may be divided into three parts. In the first, when the E. M. F. is low, the change is slight. The curve then becomes very steep in the second part, the conductivity variation being rapid. The increase of conductivity, however, reaches a limit, after which there is little further change. The whole curve is thus somewhat S-shaped.

Conductivity Variation with Cyclic Variation of E. M. F.

When conducting particles of the non-recovering, positive, or iron type are subjected to sudden electric variation due to radiation, a residual effect is observed indicative of an increase of conductivity or diminution of resistance.

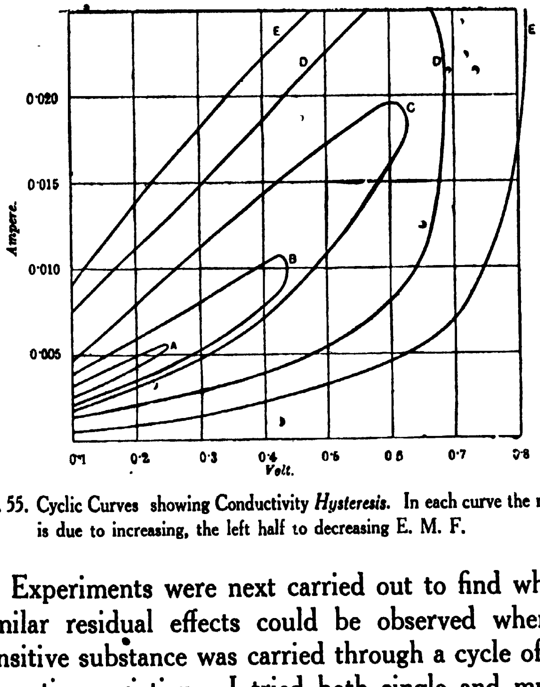


Fig. 55. Cyclic Curves showing Conductivity *Hysteresis.* In each curve the right half is due to increasing, the left half to decreasing E. M. F.

Experiments were next carried out to find whether similar residual effects could be observed when the sensitive substance was carried through a cycle of electromotive variation. I tried both single and multiple contacts.

As stated before, the E. M. F. can be continuously increased by turning the winding wheel which moves the platform uniformly in one direction; the E. M. F. is continuously diminished by turning the wheel in the opposite direction, and thus reversing the motion of the platform. By this means the receiver can be subjected to a cyclic electromotive variation through large or small range at will. I reproduce curves of cyclic variation taken with filings, when the range of electromotive variation is increased from (0·1—0·25 volt) to (0·1—0·81 volt). They will give a good general idea of the phenomena (fig. 55). A series of readings for cyclic variations taken with a single point receiver will be given later.

First, I tried the effect of cyclic variation through a small range, from 0·1 to 0·25 volt. It will be seen that the forward and return curves do not coincide, but enclose a small area. The receiver, in as far as conductivity is a criterion of its physical state, does not regain its original condition. There remains a residual conductivity variation, just as in iron there is a residual magnetism after it has been subjected to a cyclic variation of magnetising force. The residual magnetism disappears on tapping, just as the effect of residual conductivity can be dissipated by the same means.

In curve B, where the range of electromotive variation is still larger, from 0·1 to 0·43 there is a greater divergence between the forward and return curves, and the area enclosed is further increased. An interesting effect, due to *lag*, will be noticed at its far end; though the platform was on its return course, producing a diminution of E. M. F., the current nevertheless continued for a short time to rise. It is thus seen that whatever be the change to which the conductivity variation is due, it lags behind the impressed electromotive variation.

The curves C, D and E, further show that by increasing the range of electromotive variation, the area enclosed between the forward and return curves becomes considerably increased.

I give below detailed readings taken on two occasions with a single point iron receiver, (1) when the range of cyclic variation was small, (2) when the range was comparatively large (*c.f.* Tables IV and V).

Table IV.—Showing the Variation of Current and Resistance with Cyclic Electromotive Variation of Small Range

E. M. F. in volt.	Galvanometer readings. 1*dn* = 1/10⁶ amp.		Resistance in ohms.	
	Direct.	Return.	Direct.	Return.
0·05	10	12	5,000	4,166
0·10	25·5	27	3,920	3,703
0·15	47	49·5	3,191	3,030
0·20	70	75·5	2,856	2,648
0·25	103	114·5	2,427	2,183
0·30	171	197·5	1,754	1,520

It has been shown that the resistance of the receiver at the higher E. M. F. is less than that at the lower. As the E. M. F. is reduced by the reversed motion of the slider, there is a tendency towards the recovery of the higher resistance which it had at the lower E. M. F. The recovery, however, is not perfect, owing to hysteresis. The recovery is more incomplete if the critical E. M. F. had been exceeded.

There is thus a residual after-effect. In the case given, the initial resistance was 5,000 ohms, and the resistance after cyclic variation through a range of 0·25 volt was 4,166 ohms, or 8/10ths of its original value.

The lag and creeping effects are also noticeable in the forward and return readings.

While the slider moved up to 0·30 volt, the immediate galvanometer reading was 171 divisions, and by the time the slider had commenced its backward movement to the left (producing a diminution of E. M. F.), the current value had risen from 171 to 197·5; the conductivity had gone on increasing, the resistance having fallen from 1,754 to 1,520 ohms.

I now give a table of results for electromotive variation of wider range from 0·1 to 0·6 volt.

Table V.—Showing the Current and Conductivity Variation of a Single-point Iron Receiver, due to Cyclic Electromotive Variation of Comparatively Large Range but Short of Critical Point

E in volt.	G. deflection, 1 $dn = 1/10^6$ amp.		Resistance in ohms.	
	Direct.	Return.	Direct.	Return.
0·05	1·5	13	33,333	3,846
0·20	↓ 8	58 ↑	↓ 25,000	3,448 ↑
0·35	34	145	10,294	2,414
0·50	154	346	3,246	1,445
0·60	320 →		1,875 →	

In the previous case it was shown that with a cyclic variation of the moderate range of 0·25 volt, the resistance was reduced to 8/10ths; in this case, at double the range, the reduction is very much greater, for the resistance falls to nearly 1/10th of its original value.

This confirms the conclusion previously made that the greater the range of electromotive variation the greater is the reduction of resistance.

Self-Recovering Receiver

It has been shown that receivers which exhibit a diminution of resistance under electric radiation give a characteristic curve which is concave to the axis representing the current, and that in the non-recovering type noticed hitherto, the forward and return curves do not coincide, but enclose an area. I was now interested in finding out what would be the peculiarities of the characteristic curve of receivers showing self-recovery.

I have, as previously mentioned, described a self-recovering receiver of the negative type, made of silver particles. I also succeeded in constructing a self-recovering single point receiver of the positive type,

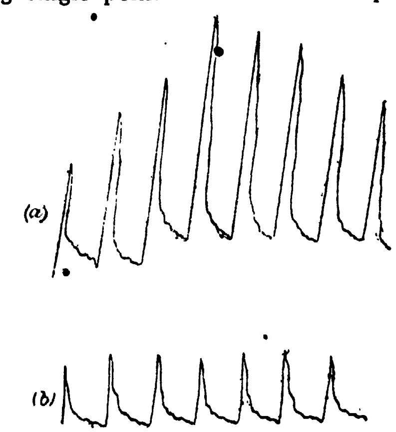


Fig. 56. Response Curves to Single Flashes of Radiation in Self-Recovering Receiver.

the successive responses of which to brief flashes of radiation are given in figure 56.

In working with receivers which have been at rest for long periods it is often noticed that the response is at first feeble. The sensitiveness soon improves, and may even become excessive ; it finally settles down to a moderate and uniform sensitivity. All these phases are well seen in fig. 56 where (*a*) exhibits the preliminary stages, and (*b*) the steadier condition, with more uniform response. The up-curves show the increase of current under the flash of radiation, and the falling and concave portions, the recovery on the cessation of radiation. In self-recovering receivers of the negative type the response curves are the reverse of these, in the sense of the reflected image in a mirror.

The Characteristic Curve of the Self-recovering Receiver of Positive Type

I now subjected the self-recovering receiver to a continuously increasing electromotive variation, and

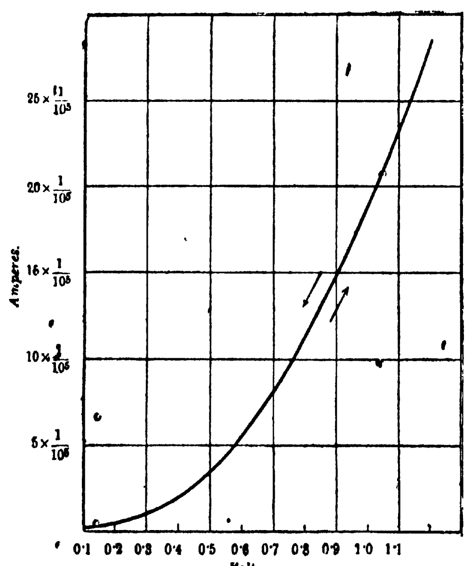


Fig. 57. Characteristic Curve of Self-Recovering Receiver of Positive Type.

traced the curve. I was not prepared, however, for results so remarkably perfect. In the present case I was not only able to obtain the most important and characteristic effects with great ease and certainty, but also to repeat them, the results of successive experiments being practically identical.

The extreme regularity of the observed effect is seen at a glance in figure 57. I give below a table which shows how continuously the resistance is diminished under increasing E. M. F.

Table VI.—Showing Variation of Current and Resistance in Self-recovering Positive Receiver with Increasing E. M. F.

E. M. volt.	Current. 5 $dn=1/10^5$ amp.	Resistance in ohms.
0·2	2	50,000
0·3	5	30,000
0·4	10	20,000
0·5	17	14,700
0·6	27	11,100
0·7	40	8,750
0·8	55	7,270
0·9	73	6,160
1·0	94	5,320
1·1	115	4,780
1·2	141	4,245

It will be seen that whereas at 0·2 volt the resistance is 50,000 ohms, at 1·2 volt it has undergone an uninterrupted fall to 4,245 ohms, or 1/12th of its original value. There has been no sudden breakdown at any intermediate point.

Figure 58 exhibits the variation of resistance under increasing E. M. F. described in the table VI.

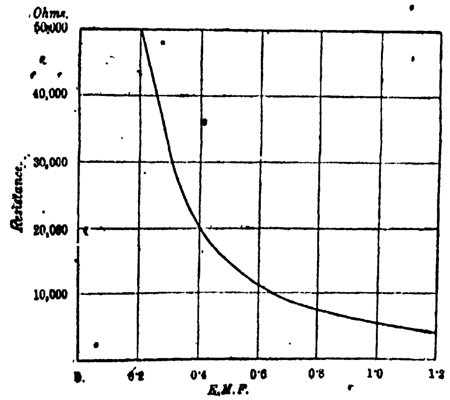


Fig. 58. Curve showing the Variation of Resistance with Increasing E. M. F.

Effect of Cyclic Variation of E. M. F.

But the most astonishing thing about the action of the receiver was that in taking the return curve, I found it practically coinciding *in every part* with the forward curve, so that when the E. M. F. was brought back to its initial value of 0·1 volt, the receiver had completely returned by its original path to its first condition, there being no residual effect. I repeated the experiment many times in succession, but the curves obtained, whether forwards or backwards, were in every case merely superposed on the original. Since the condition of the receiver is exactly the same after many cycles as at the beginning, it is evident that the conductivity variation could not be due essentially to any chemical change, for such changes are irreversible.

The increase of conductivity with increase of E. M. F. is not due to any sudden breakdown, such as fusion between the contact surfaces, for the process described above is anything but abrupt. Again, fusion would have produced a permanent conductivity change, but in the case under review the change is not permanent. Thus, for example, when the applied E. M. F. was 0·2 volt, the current was represented by a deflection of two divisions, the resistance being 50,000 ohms. When the E. M. F. was raised to 0·7 volt, the current increased to 40 divisions, indicating a diminution of resistance which remained at the definite value of 8,750 ohms. If the E. M. F. was again reduced to its original value of 0·2 volt the current was once more two divisions, and the resistance rose to exactly its original value of 50,000 ohms. It would thus appear that—

(1) For a particular E. M. F. there is a definite value of conductivity.

(2) When in a given part of the curve the E. M. F. is increased by a definite amount, the conductivity is also increased in a definite manner. The increased stress produces a definite conductivity distortion, and on the removal of the stress there is a quasi-elastic recovery of its original conductivity.

(3) As the seat of these changes is in the molecular layers at the definite single-point contact, it would appear that the conductivity variation and its recovery are due to molecular distortion and subsequent elastic recovery.

What has been said above of the conductivity change under electromotive variation and the complete recovery is true only when the cycle is completed at a moderate speed, during which, time is allowed for the completion of, or the recovery from, the induced change. But if the cyclic variation be carried out with very great rapidity, the phenomenon of lag comes into play. The conductivity variation then lags behind the impressed electromotive variation, and the receiver does not instantaneously recover its original resistance.

For example, in the case of the self-recovering receiver which at 0·2 volt gave a current represented by two galvanometer divisions, the resistance being equal to 50,000 ohms, the cyclic electromotive variation was quickly carried through the range from 0·2 volt to 1·2 volt and back to 0·2 volt, the immediate value of the current at this last point was not two, but six, divisions of the galvanometer. Thus the receiver, owing to lag, does not instantaneously recover its original resistance; the deflection, however, soon creeps back to two, exhibiting a complete recovery. This characteristic of self-recovery is also exhibited by rapid electromotive variation as under electric radiation (see fig. 56).

Space allows only a brief reference to the characteristic cyclic curve of negative class of substance exemplified by potassium. In this we are presented with the extraordinary phenomenon that an increase of E. M. F. is attended by a diminution of current, so that at a critical E. M. F. the current disappears altogether.

Summary

1. Under the action of electric radiation the conductivity of metallic particles exhibits variation. In the positive class, like iron, there is an increase, and in the negative, like K, a diminution, of conductivity. Each class again falls into two sub-classes, (*a*) sensitive substances which exhibit self-recovery, and (*b*) sensitive substances which do not. In the case of self-

recovering substances the conductivity distortion varies with the intensity of radiation. Under the continued action of radiation, the distortion attains a maximum, balanced by a force of restitution, and on the cessation of radiation there is an elastic self-recovery.

2. The three classes of substances, positive, negative and neutral, may be distinguished by their characteristic curves.

3. The change produced in the sensitive substance by the action of radiation is not, normally speaking, chemical.

4. The conductivity change is produced, not only by very rapid, but also by comparatively slow electric variation. Generally speaking, all the conductivity variation effects produced by electric radiation can be reproduced by comparatively slow cyclic electromotive variation.

5. These conductivity changes under cyclic E. M. variation can be continuously recorded by means of the Conductivity Recorder.

6. Electric conduction in metallic particles sensitive to electric radiation does not obey Ohm's law. The conductivity is not constant and independent of the E. M. F., but varies with it. In the positive class the characteristic curve, in which the ordinates represent the currents, and the abscissæ the E. M. F., is concave to the axis of the current. The conductivity increases *continuously* with the increasing E. M. F. The variation of the conductivity in the lower portion of the curve is small, but increases with great rapidity in the upper portion. In the negative class of substance the characteristic curve is convex to the axis of the current.

7. The curve obtained with strong, is steeper than that with feeble, initial current.

8. There is found, especially when the initial current is feeble, a critical E. M. F., at which the conductivity change becomes so rapid as to produce an almost abrupt bend in the curve. Stronger initial current appears not only to lower the critical point, but also to mitigate the abruptness of this change.

9. The effect of E. M. F. in modifying the conductivity of the surface layer is well seen in self-recovering substances. There is a definite conductivity corresponding to a definite E. M. F. As the E. M. F. is increased, the sensitive molecular layer is strained, and a definite increase of conductivity produced. When the increased stress is removed, the corresponding strain also disappears, and there is an elastic recovery to its former molecular and conductive state. Hence, when it is carried through a complete cycle of electromotive variation, with moderate speed, the forward and return curves coincide, and the substance regains, at the end of the cycle, its original molecular condition.

10. This is the case where there is complete recovery on the removal of the stress. With non-recovering substances we find an outstanding residual effect. In a curve taken with cyclic electromotive variation, the forward and return curves do not coincide, but enclose an area. There is a hysteresis. The larger the range of the electromotive variation the greater is the area enclosed. There is a residual conductivity variation, at the end of the cycle, which may be dissipated by mechanical vibration.

(*British Association at Glasgow, Section A, September* 1901.)

XVIII

ON THE SIMILARITY OF EFFECT OF ELECTRICAL STIMULUS ON INORGANIC AND LIVING SUBSTANCES

In working with receivers for electric waves, I found that under continuous stimulation by the oncoming message, the sensitiveness of the metallic detector disappeared. But after a sufficient period of rest it regained once more its normal sensitiveness. In taking records of successive responses, I was surprised to find that they were very similar to those exhibiting fatigue in the animal muscle. And just as animal tissue, after a period of rest, recovers its activity, so did the inorganic receiver recover after an interval of rest.

Thinking that prolonged rest would make the receiver even more sensitive, I laid it aside for several days and was astonished to find that it had become inert. A strong electric shock now stirred it up into readiness for response. Two opposite treatments are thus indicated for fatigue from overwork, and for inertness from long passivity.

A muscle-curve registers the history of the fundamental molecular change produced by excitation in a living tissue, exactly as the curve of molecular reaction registers an analogous change in an inorganic substance. The two represent the same thing; in the latter the molecular upset is evidenced by the change of conductivity, while in the former it is manifested by the change of form. We have thus means of studying molecular reaction produced by stimulus of varying frequency, intensity and duration. An abyss separates the phenomena of living matter from those of inanimate matter. But if we are ever to understand the hidden mechanism of the animal machine it is necessary to face numerous difficulties which at present seem formidable.

I shall now describe the results of comparative study of the curves of molecular reactions of inorganic and living substances. For the former I will take the response of magnetic oxide of iron (Fe_3O_4) to the action of stimulus of electric radiation. Suppose we start with this substance in its normal condition with moderate conductivity, the galvanometer deflection being 50 div., under a definite electromotive force. The deflection of 50 will, therefore, indicate the normal conductivity. Next, under the stimulus of electric waves the induced molecular change causes an increase of conductivity represented by the larger deflection of 100. On the cessation of the stimulus there is a recovery, the galvanometer deflection returning from 100 to the original value 50. The suspended coil of the galvanometer thus moves in response to the varying molecular change induced in the sensitive substance by the action of stimulus. The invisible molecular change is thus revealed by the visible deflection of the galvanometer coil. Curves of molecular change due to electrical stimulation may thus be obtained with galvanometer deflections as ordinates and the periods of stimulation and recovery as abscissæ.

Response to a Single Stimulus

The curve given in fig. 59 represents the effect of instantaneous stimulus on the inorganic receiver. There is a latent period, the response taking place a short time after the incidence of the stimulus; the response continues for a short period even after the cessation of stimulation; it attains a maximum after which

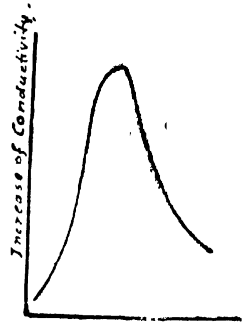


Fig. 59. Curve for Fe_3O_4.

the substance begins to recover, at first quickly, then more slowly. In all this, an analogy is found with the response curve of muscles, in which also there is a short phase of latent period, a phase of increasing action and a phase of recovery.

Superposition of Stimuli

Three sets of experiments were carried out (1) on the effect of succession of maximum stimuli; (2) on the summation-effects of medium stimuli with slow intermittence; and (3) on the summation-effects of rapid intermittence.

Maximum stimulation.—By bringing the radiator sufficiently near the inorganic receiver, a maximum effect was observed, the deflection being 230 divisions. Before the substance could recover to any extent, a second stimulus was superposed. This produced no further deflection, but when the second stimulus was applied after recovery, then the second deflection was the same as the first, *i.e.*, 230 divisions.

Medium stimulus, slow intermittence.—In this set of experiments, the radiator was moved further away so that the intensity of the stimulus was moderate; the successive flashes of radiation were applied at intervals of two seconds. These moderate excitations are found to be summated and when in slow succession, the effect of each shock can be distinguished as the steps in the ascending curve, as in fig. 60 (*a*).

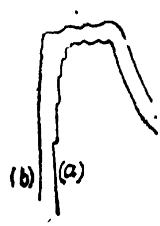


Fig. 60. Superposition of Effects. (*a*) Effect due to Slow Intermittence. (*b*) Tetanic Effect due to High Frequency Intermittence.

Rapid intermittence.—When the stimuli follow each other with great rapidity, the intermittent effects are fused together; the rising curve is found to be unbroken and the effect may be described as 'tetanic' as in fig. 60 (*b*).

The response curves of muscles under the above conditions are similar to the above.

Opposite Effects of Strong and Feeble Stimulus

The response of many inorganic receivers was found to exhibit the peculiarity that while moderate intensity of stimulus produced the normal response of a given sign, a feeble stimulus elicited the opposite reaction, the sign of response being reversed (*cf.* p. 137). I succeeded later in demonstrating the occurrence of similar reactions in living tissues, as for example in the physiological action of drugs, which may be regarded as chemical stimuli.' A small 'dose' in such cases is often found to give rise to an effect precisely opposite to that produced by a large dose.

Effect of Variation of Temperature

Variation of temperature produces a marked effect on the response of muscle. At a low temperature the response is very sluggish and the amplitude of response is very much reduced. With rise of temperature the size of response increases and the period of recovery becomes quickened (fig. 61 *a*, *b*). Above a certain optimum the response becomes diminished.

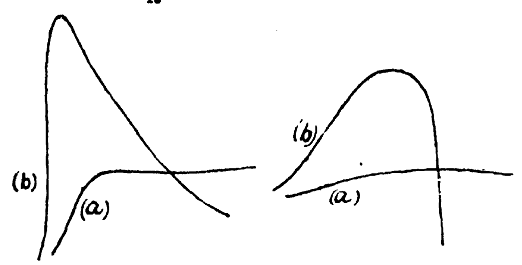


Fig. 61. Effect of Variation of Temperature on Response.
Response of Muscle, left; Response of Inorganic receiver, right. (*a*) response at low temperature (*b*) at a higher temperature.

Parallel effects are observed in the response of the inorganic receiver. The curve *a* to the right represents the response of the magnetic oxide of iron receiver when cold; the deflection was moderate and the recovery was extremely slow. On raising the temperature of the receiver to about 15° C. above that of the room, the amplitude of the response was found to be very much increased—nearly threefold.

The recovery became rapid specially in the first part, complete recovery taking place in the course of 75 secs. When the temperature was raised to 100° C., the response became greatly reduced. It is thus seen that a rise of temperature up to an optimum increases the amplitude of response and hastens the recovery in both inorganic and living substances.

Effect of Chemical Substances

Traces of certain substances are found to produce an extraordinarily great increase in the sensibility of the inorganic receivers; these act like stimulants. There are other substances which abolish the sensibility acting like "poisons."

In all the phenomena described above there is no break of continuity. It is difficult to draw a line and say 'here the physical phenomenon ends and the physiological begins' or "that is a phenomenon of dead matter and this a vital phenomenon peculiar to the living"; such lines of demarcation do not exist.

I shall in a future occasion describe a different method namely that of electromotive variation for obtaining the response of inorganic matter, and demonstrate the continuity of response in the living and the non-living.

(*International Congress of Science, Paris* 1900.)

XIX

THE RESPONSE OF INORGANIC MATTER TO MECHANICAL AND ELECTRICAL STIMULUS

Certain changes take place when a living muscle is pinched or an electric shock passed through it. A responsive twitch is produced; the muscle is changed in form, becoming shorter and broader; the particles of the living substance are strained under the stimulus. The effect of the shock then disappears, and the muscle relaxes into its usual form.

This sudden change of form then, is one, but not the only mode of response of a living substance to external stimulus. Under external stimulation the muscle is thrown into a state of strain. On cessation of the stimulus it automatically recovers. As long as it is alive, so long will it respond and recover, being ready again for a new response. This brief disturbance of the living poise, to be immediately restored to equilibrium of itself, is quite unlike the rolling of a stone downhill from a push. For the stone cannot regain its original position; but the living tissue at once reasserts its first stable poise on the cessation of stimulus. Thus a muscle, as long as it is alive, remains ever-responsive. It is in intimate relation with the forces by which it is surrounded, always responding to, and recovering from, the multitudinous stimuli of its physical environment.

The living body is thus affected by external stimuli—mechanical shock, electrical stimulus, and the stimuli of heat and light—which evoke in it corresponding responses.

In the case of the contraction of muscle by mechanical or electric shock, the effect is very quick, and the contraction and relaxation take place in too short a time for detailed observation by ordinary means. Physiologists, therefore, use a contrivance by which the whole process may be recorded automatically. This consists of a lever arrangement, by which the contracting muscle writes down the history of its change, and recovery from that change. The record may be made on a travelling band of paper, which is moving at a uniform rate (fig. 62). A single response to a single stimulus consists of a contractile up-curve followed by the down-curve of recovery, the entire process being completed within a definite period of time. This autographic record gives us the most accurate information as to the characteristic properties and condition of the muscle. It gives us, too, all its individual characteristics.

Just as one wave of sound is distinguished from another by its amplitude, period, and form, so are the curves of different muscles distinguished. For example, the period for tortoise muscle may be as long as several seconds, whereas the period for the wing of an insect is as short as $\frac{1}{300}$th of a second. In the same muscle, again, the form of the curve may undergo changes from fatigue, or from the effects of various drugs. In the autographic record of the progressive death of a muscle, the graph is vigorous at first, but grows lethargic on the approach of death. In some strange way the molecules lose their mobility, rigidity supervenes, and the record of the dying muscle comes to an end. We may thus find out the effects of various external influences by studying the changes in the muscle-curve.

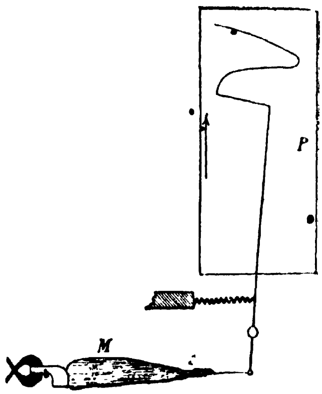


Fig. 62. Mechanical Lever Recorder. The muscle *M* with the attached bone is securely held at one end, the other end being connected with the writing lever. Under the action of stimulus the contracting muscle pulls the lever and moves the tracing point to the right over the travelling recording surface *P*. When the muscle recovers from contraction, the tracing point returns to its original position. See on *P* the record of muscle curve.

We may stimulate the living substance in various ways—by light, or by thermal, chemical, electrical, or mechanical stimuli. Of these, the electric means of stimulation is the most convenient, whereas the mechanical causes fewest complications. With regard to the response of living substances, the most important matters for study are the responses to single stimulus and the modification of response by fatigue and by drugs.

A *single shock* causes a twitch, but the muscle soon recovers its original form. The rising portion of the curve is due to contraction, whereas the falling portion exhibits recovery (see curve in fig. 62).

When the muscle is continuously excited it gets fatigued. The height of the curve becomes continuously less.

Drugs may act as stimulants, or produce depression, according to their nature. As extreme cases of such depressing agents we may instance poisons, which kill the response of living tissue. All signs of irritability then disappear.

Other Modes of Response

This mechanical method of studying the response of living substances is, however, very limited in its application. For example, when a piece of nerve is stimulated, there is no visible change. When light falls on the retina there is no change of form, but it responds by transmitting to the brain a visual impulse. What, then, is this visual impulse which is sent along the optic nerve, causing the sensation of light?

Thanks to the work of Homgren, Dewar, McKendrick and others, it is possible to answer this question. If we excise an eye, say of a frog, and substitute a galvanometer in the visual circuit in the place of the perceiving brain, it is then found that each time a flash of light falls on the eye there is produced an electric response—that is to say, there is a sudden production of a current, which ceases on the cessation of light-stimulus. Stronger light produces stronger electric response in the galvanometer, just as it produces stronger visual sensation in the brain.

The visual circuit is therefore like an electric circuit. The retina is the sensitive element. The nerve is the conductor. The brain like the responding galvanometer is a detector of the impulse. Unless these three elements are in good order, no light-message can be perceived. We must have a sensitive retina, and the conducting nerve, free from injury. Finally, just as the galvanometer will fail to detect a current if it is injured by rough usage, so also after a violent blow, the brain will no longer perceive, though the terminal organ, the retina, and the connecting optic nerve may be intact.

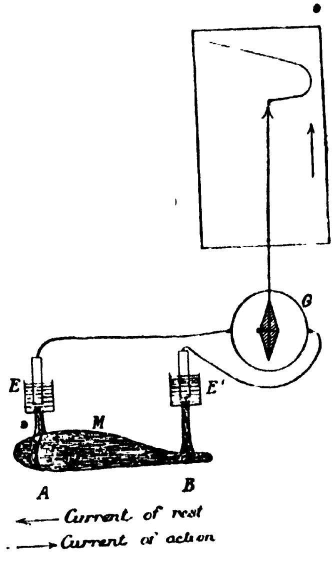


Fig. 63. Magnetic Lever Recorder. *M* muscle; *A* uninjured, *B* injured ends. *E E'* non-polarising electrodes connecting *A* and *B* with galvanometer *G*. Stimulus produces "negative variation" of current of rest. Index connected with galvanometer needle records curve on travelling paper (in practice, moving galvanometer spot of light traces curve on photographic plate). Rising part of curve shows effect of stimulus; descending part, recovery.

Electric Response

If we take a piece of living muscle whose surface is uninjured, then any two points A and B on such a surface being in similar molecular conditions, their electrical level or potential will be the same. They are *iso-electric.* No current will be exhibited by the indicating galvanometer when two non-polarisable electrodes connected with it are applied to A and B. But if one of the two points, say B, be injured by a cut, or burn, then, the conditions of A and B being different, there will be a difference of electric level or potential between them, and a current will flow from the injured to the uninjured, that is from B to A (fig. 63). This current remains approximately constant as long as the muscle is at rest, and is for this reason known as "current of rest." As it is primarily due to injury, it is also known as "current of injury." If now the muscle be thrown into an excitatory state* by stimulus, there will be a greater relative change at the uninjured A, and the original difference of electric level will be disturbed. There is then a *negative* variation or diminution of the original current of rest. This negative variation or "action current" constitutes the "response," the intensity of which increases with the intensity of the stimulus.

If a piece of muscle be taken, and simultaneous records of its response be made by the mechanical and electrical recorders, it will be found that the one is practically a duplicate of the other.

Response in Plants

I find that the electric response seen in animal tissues is also strongly exhibited by the tissues of plants. Various parts of plants—leaves, stems, stalks, and roots

* The excitatory reaction is, in the case of some living substances, of a more or less local character. In others, as nerves, it may be conducted to distant points.

—give electric response. In some there is a rapid fatigue, whereas in others there is little fatigue. A more detailed account of these responses and their modifications by anæsthetics, poisons, and other agencies will be found in a subsequent paper.

Universal Applicability of the Test of Electric Response

Nothing has yet been said of the advantage of the electrical over the mechanical method of obtaining response. As has been said before, the mechanical method is limited in its application. A nerve, for example, does not undergo any visible change of form when excited, and its response cannot therefore be detected by this method. But by the electrical method we are able to detect, not only the response of muscles, but also of all forms of living tissue.

The intensity of electrical response is also a measure of physiological activity. When this is diminished by anæsthetics, the electrical responses also become correspondingly diminished. And when the living tissue is in any way killed, the electrical response disappears altogether.

Thus, electrical response is regarded as the criterion between the living and non-living. Where it is, life is said to be; where it is not found, we are in presence of death, or else of that which has never lived: for in this respect there is a great gulf fixed between the organic living and the inorganic or non-living. The phenomena of the inorganic are supposed to be dominated merely by physical forces, while on the other side of the chasm, in the domain of the living, inscrutable vital phenomena, of which electric response is the sign-manual, suddenly come into action.

But is it true that the inorganic are irresponsive, that forces evoke in them no answering thrill? Are their particles for ever locked in the rigid grasp of immobility? As regards response, is the chasm between the living and inorganic really impassable?

Inorganic Response

Let us take a piece of thin wire from which all strains have been removed and hold it clamped in the middle at C (fig. 64).

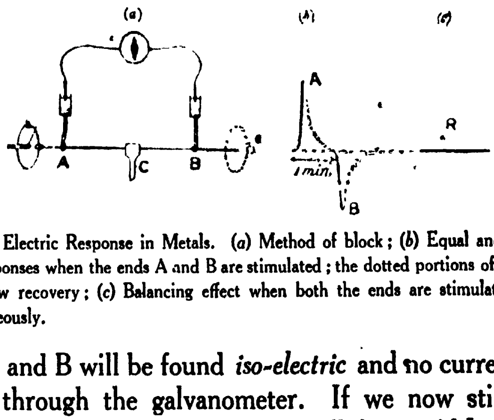


Fig. 64. Electric Response in Metals. (*a*) Method of block; (*b*) Equal and opposite responses when the ends A and B are stimulated; the dotted portions of the curve show recovery; (*c*) Balancing effect when both the ends are stimulated simultaneously.

A and B will be found *iso-electric* and no current will pass through the galvanometer. If we now stimulate the end A by a tap, or better still by rapid torsional vibration, a " current of action " will be found to flow in the wire in one direction. Stimulation of B on the other hand, gives rise to a current in the opposite direction. The object of the block C is to prevent the molecular disturbance produced by stimulus at one end of the wire from reaching the other.

Quantitative stimulation is applied by producing a sudden torsional vibration, say of 90°, to the end A, with the result of an up-response of the galvanometer; on application of similar stimulus to the end B, there is produced an equal and opposite response (fig. 64). If now both the ends A and B are stimulated simultaneously, the responsive electromotive variation at the two ends will continuously balance each other and the galvanometer spot will remain stationary. Fig. 65 gives the record of series of equal and opposite responses by alternate stimulation of A and B.

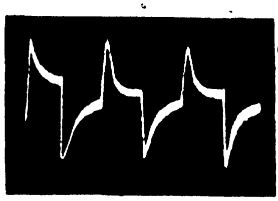


Fig. 65. Photographic Record of Equal and opposite Responses exhibited by stimulations of A and B (Tin).

The similarities of response of inorganic and living substances are now sufficiently evident. We have to extend the inquiry to see whether this similarity extends to this point only, or goes still further. Are the response-curves of the inorganic modified by the influence of external agencies, as the living responses are found to be?

Effect of Superposition of Stimuli

It has been said that under rapidly succeeding stimuli, the intermittent effects of single shocks become fused, and the muscle responds by an almost unbroken tetanic curve (fig. 66). If the frequency is not sufficiently great, there is an incomplete tetanus and the response-curve becomes jagged.

The very same thing occurs in metals. I subject the wire to quickly succeeding vibrations. The curve rises to its maximum; further stimulation adds nothing to the effect, and the deflection is held, as it were rigid,

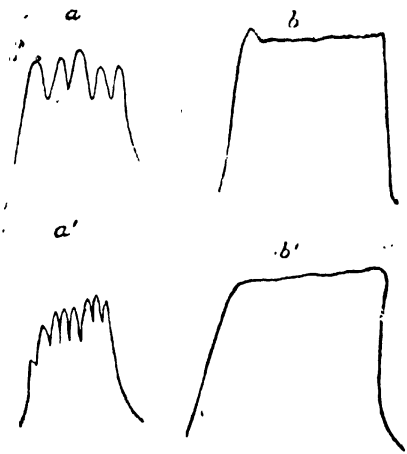


Fig. 66. Effects analogous to (*a*) incomplete and (*b*) complete tetanus in tin. (*a'*) Incomplete and (*b'*) complete tetanus in muscle.

so long as the stimulation is kept up. With lesser frequency of stimulation the tetanus is incomplete, and the curve becomes jagged (fig. 66).

Fatigue

Amongst living substances the nerve is practically indefatigable. Successive curves are exactly similar. Muscles, however, exhibit fatigue, which disappears after a period of rest.

Inorganic substances likewise exhibit fatigue specially after prolonged action. The fatigue curve here reproduced was obtained from tin that had been subjected to very prolonged stimulation; its remarkable similarity to the curve of fatigue in muscles will be at once apparent (fig. 67). Fatigue in metal is also removed by a period of rest.

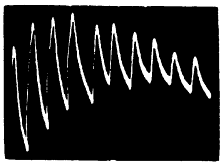


Fig. 67. Photographic record of fatigue in tin.

Stimulus of Light

I have in this investigation mainly used the mechanical form of stimulation as being the simplest and giving rise to fewest complications. Time does not allow of my entering here upon the subject of the response under electric stimulation. I may, however, say a few words on the effect of the stimulus of light.

If one of the sensitised wires in the cell already described be subjected to light it gives an electric response, and under certain circumstances an oscillatory after-effect is seen to occur on the cessation of light. This latter fact probably explains certain phenomena of visual recurrence to be noticed presently.

Artificial Retina

The molecular strain produced by stimulus can not only be detected by the phenomena of electromotive variation, but also by conductivity variation. Acting on this principle, I have been able to construct an artificial retina constructed of galena. The sensitive receiver is placed inside a hollow spherical case, provided with a circular opening in front, in which a glass lens is placed, corresponding to the crystalline lens. You now see before you a complete model of an artificial eye. When this is interposed in an electric circuit, with a sensitive galvanometer as indicator, you observe the response to a flash of light by the galvanometer deflection. I throw red, yellow, green and violet lights upon it in succession, to all of which it responds. Note how strong is the action of yellow light, the response to violet being relatively feeble. Indeed, the most striking peculiarity of this eye is that it can see lights not only some way beyond the violet, but also in regions far below the infra-red, in the invisible regions of electric radiation. It is in fact a *Tejometer* (Sanskrit *tej*-radiation), or universal radiometer.

Observe how each flash of invisible light I am producing with this electric radiation apparatus, calls forth an immediate response, and how the eye automatically recovers without external aid. This will show the possibility of an automatic receiver which will record Hertzian wave-messages without the intervention of the crude tapping device.

This retina has, as will be seen with regard to spectral vision, an enormous range, extending far beyond the visual limits. We can, however, reduce its powers to a merely human level by furnishing it with a water lens, which, in its liquid constitution, approximates closer to the lens of the eye than does the glass substitute. In this case the invisible radiations are absorbed by the liquid, and do not reach the sensitive retina. Perhaps we do not sufficiently appreciate, especially in these days of space-signalling by Hertzian waves, the importance of that protective contrivance which veils our sense against insufferable radiance.

Binocular Alternation of Vision

I have referred to the fact that sometimes on the cessation of light, an after-oscillation is observed, which may correspond to the after-oscillations of the retina, and give a probable explanation of the phenomena of recurrent vision. When we have looked at a bright object for some time with one eye, we find, on closing both eyes, that the image alternately appears and disappears. It was while studying this subject that I came upon the curious fact that the two eyes do not see equally well at a given instant, but take up, as it were, the work of seeing, and then resting, alternately. There is thus a relative retardation of half a period as regards maximum sensation in the two retinas. This may be demonstrated by means of a stereoscope, carrying, instead of stereo-photographs, incised plates through which we look at light. The design consists of two slanting cuts at a suitable distance from each other. One cut, R, slants to the right, and the other, L, to the left (see fig. 68). When the design is looked at through the stereoscope, the right eye will see, say R, and the left L; the two images will appear superimposed, and we see an inclined cross. When the stereoscope is turned towards the sky, and the cross looked at steadily for some time, it will be found, owing to the alternation already referred to, that while one arm of the cross begins to be dim, the other becomes bright and *vice versa*. The alternate fluctuations become far more conspicuous when the eyes are closed; the pure oscillatory after-effects of the strained sensitive molecules in the retina are then obtained in a most vivid manner. After looking through the stereoscope for ten seconds or more, the eyes are closed. The first effect observed is one of darkness, due to the rebound. Then *one* luminous arm of the cross first projects aslant the dark field, and then slowly disappears; after which the second (perceived by the other eye) shoots out suddenly in a direction athwart the first. This alternation proceeds for a long time, and produces the curious effect of two luminous blades crossing and re-crossing each other. Another method of bringing out the same facts in a still more striking manner, is to look at two different sets of writing, with the two eyes. The resultant effect is a blurr, due to superposition, and the inscription cannot be read with the eyes open. But on closing them, the composite image is analysed into its component parts, and thus we are enabled to read better with eyes shut than open!

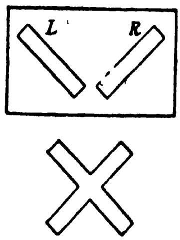


Fig. 98. Stereoscopic design to show binocular alternation of vision.

It will thus be seen how, from observing the peculiarities of an artificial organ, we are led to discover unsuspected peculiarities in our own. We stand here on the threshold of a very extended inquiry, of which I can only say that as it has been possible to construct an artificial retina, so I believe it may not be impossible to imitate also other organs of sense.

Effects of Chemical Reagents

I now return to the consideration of mechanical stimulus and the modification of its responses, as shown by metals. We have seen the remarkable parallelism between organic and inorganic responses under various conditions. There still remains the study of the effects of chemical reagents. Drugs profoundly modify the response of living substances; the effects of which may be classified under three classes, some acting as stimulants, others as depressors, and yet others again as poisons, by which response is permanently abolished. Amongst the last may be mentioned mercuric chloride, oxalic acid and others. Again, drugs which in large doses become poisons, may, when applied in small quantities, act as stimulants.

It may be thought that to these phenomena, inorganic matter could offer no parallel. For they involve possibilities which have been regarded as exclusively physiological. Accustomed in the animal to find the responsive condition transformed into the irresponsive state at the moment of death, we look on this sequence as peculiar to the world of the living. And on this fact is based the supreme test by which physical and physiological phenomena are differentiated. That only can be called living which is capable of dying, we say, and death can be accelerated by the administration of poison. The sign of life as given by the electric pulses then wanes, till it ceases altogether. Molecular immobility—the rigor of death—supervenes, and that which was living is no longer alive.

Is it credible that we might, in like manner, kill inorganic response by the administration of poison? Could we by this means induce a condition of immobility in metals, so that, under its influence, their electric responses should wane and die out altogether?

Before we attempt the action of poisons let us study the exciting effect of stimulants. You observe the normal extent of response under successive uniform stimuli applied to one wire of the cell. I now add a few drops of diluted solution of sodium carbonate and you observe the growing exaltation of the response. (fig. 69).

I now pass on to the effect of poisons. Any of the substances already enumerated may be used as the

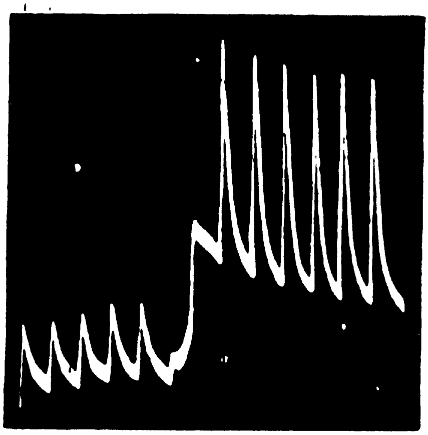


Fig. 69. Stimulating action of $Na_2 CO_3$ on tin.

toxic agent. After obtaining the normal response I apply a poisonous solution of oxalic acid. The electric response is now completely killed and all our efforts, by intense stimulation to reawaken them, fail (fig. 70).

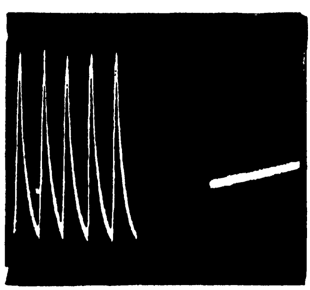


Fig. 70. Abolition of Response by Oxalic acid.

But we may, sometimes at least, by the timely application of a suitable antidote, revive the dying response, as I do now. See how the lethargy of immobility passes away; the electric throb grows stronger and stronger, and the response in the piece of metal becomes normal once more.

There remains the very curious phenomenon, known not only to students of physiological response but also in medical practice, that of the opposite effects produced by the same drug when given in large or in small doses. Here too we have the same phenomenon reproduced in an extraordinary manner in inorganic response. The same agent which becomes a poison in large quantities thus acts as a stimulant when applied in small doses.

I have shown you this evening autographic records of responses of the living and non-living. How similar are the writings! So similar indeed that you cannot tell one from the other apart. We have watched the responsive pulses wax and wane in the one as in the other. We have seen response sinking under fatigue, becoming exalted under stimulants, and being "killed" by poisons, in the non-living as in the living.

Amongst such phenomena, how can we draw a line of demarcation, and say, "here the physical process ends, and there the physiological begins"? No such barriers exist.

Do not the two sets of records tell us of some property of matter common and persistent? Do they not show us that the responsive processes, seen in life, have been foreshadowed in non-life?—that the physiological is, after all, but an expression of the physico-chemical, and that there is no abrupt break, but a continuity?

If it be so, we shall turn with renewed courage to the investigation of mysteries which have long eluded us. For every step of science has been made by the inclusion of what seemed contradictory or capricious in a new and harmonious simplicity. Her advances have been always towards a clearer perception of underlying unity in apparent diversity.

(Friday Evening Discourse, Royal Institution, May 1901)

XX

ON ELECTROMOTIVE WAVE ACCOMPANYING MECHANICAL DISTURBANCE IN METALS IN CONTACT WITH ELECTROLYTE

Take a rod of metal, and connect the two points A and B with a galvanometer by means of non-polarisable electrodes. (Fig. 71*a*.) If the point O is struck, a wave of molecular disturbance will reach A and B. It will be shown that this is attended by a wave of electric variation. The mechanical and the attendant electrical disturbance will reach a maximum and then gradually subside. The resultant effect on the galvanometer will be due to $E_A - E_B$ where E_A and E_B are

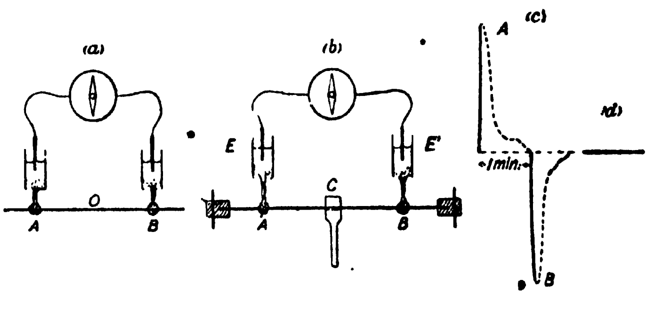


Fig. 71. In (*a*) mechanical disturbance at O produces similar electrical variations at A and B; there is no resultant effect. In (*b*) owing to a clamp, molecular disturbance initiated at A cannot reach B. A tap or vibration imparted to the end A produces responsive current which flows in the wire from the unexcited B to the excited end A. Disturbance at B gives rise to a current in the opposite direction. (*c*) gives the record of the response to equal stimuli applied to A and B. The ascending part of the curve shows the effect of stimulus, the falling part shows recovery. (*d*) Simultaneous stimulation of A and B gives no resultant response. (In the records dotted lines represent recovery.)

the electric variations induced at A and B. The electric changes at A and B will continuously balance each other, and the resultant effect on the galvanometer will be zero, when the mechanical disturbance reaches A and B at the same time and with the same intensity, when the molecular condition is similar at the two points, and when the rate of rise and subsidence of disturbance is the same at the two points. In order that a resultant response may be exhibited, matters have to be so arranged that (1) the disturbance reaches one point, say A and not B, and *vice versâ*. This may be accomplished by the method of block. Again, a resultant differential action may be obtained even when the disturbance reaches both A and B, if the electrical excitability of one point is relatively exalted or depressed by physical or chemical means. Besides the method of the block there are thus two other means of obtaining a resultant response, (2) by the method of relative exaltation, (3) by the method of relative depression.

Method of Block

The electromotive effect described below can be obtained with all metals. A piece of " tin " wire (an alloy of tin and lead used as electric fuse) will be found to give very good results. A specimen of wire 1 mm. in diameter, 10 cm. in length, is mounted in the apparatus. Two strips of cloth moistened with water or dilute salt solution are securely tied round two points A and B. Electric connections are made with the indicating galvanometer by means of non-polarisable electrodes (Zn in ZnSO solution). Special precautions are taken so that there is no variation of contact. If a sharp tap be now given near A, a transitory electrical current in response to the disturbance will be found to flow round the circuit, in a definite direction. Disturbance of B gives rise to a current in the reverse direction. For quantitative measurement it is necessary to have the intensity of stimulus maintained uniform, or increased or decreased in a definite manner. Instead of a tap, the stimulus of torsional vibration is more satisfactory. By maintaining the amplitude of vibration constant, or increasing or decreasing the amplitude, we can either keep the stimulus constant, or increase or decrease it in a quantitative manner. I shall first describe some of the typical results which may be obtained with the simple "straight wire form" of the apparatus. Worked with care it gives consistent and good results. For quantitative measurements requiring the greatest exactitude the "cell form," to be presently described, will be found more satisfactory.

Recording Apparatus.—The galvanometer used is a sensitive dead-beat D'Arsonval. The records are taken by means of a cylindrical modification of the response recorder described in a previous paper, or by means of photography. In the latter method, a clockwork moves the photographic plate at a uniform rate and a curve is traced on the plate by the moving galvanometer spot of light. The disturbance of molecular equilibrium caused by the stimulus is attended by an electromotive variation, which gradually disappears on the restoration of molecular equilibrium. The rising portion of the response curve shows the electromotive effect, due to stimulus, and the falling portion the recovery. The ordinate represents the electromotive variation, and the abscissa the time.

Experiments for Exhibition of Balancing Effect

If the wire had been carefully annealed, the molecular conditions of its different points are approximately the same. The wire will therefore be practically iso-electric throughout its length. If the wire be now held near the middle by the clamp, and a vibration through an amplitude of, say, 90° be given to the end A, an upward deflection will be produced; an equal and opposite deflection will be produced by similar vibration of B (fig. 71, *c*). If both the ends are simultaneously vibrated, the electromotive variation at the two ends will continuously balance each other, and the galvanometer spot will remain quiescent (fig. 71, *d*). The clamp is next removed, and the wire vibrated as a whole; the stimulation of A and B being the same, there is no resultant deflection. Having found the balancing point for the clamp (which is at or near the middle), if the clamp be now shifted to the left, on simultaneous vibration of A and B, the A effect will relatively be the stronger (inasmuch as the torsional vibration of A is increased and that of B decreased), and there is produced a resultant upward deflection. Thus keeping the rest of the circuit untouched, by merely moving the clamp from the left, past the balancing position to the right we get either a positive or zero or a negative resultant effect. This can be repeated any number of times. The experiment shows further that when the amplitude of vibration is kept constant, the intensity of electromotive effect is increased by shortening the wire. The normal direction of the current of response in the wire is in the majority of metals, from the relatively less to the relatively more excited point.

The form of the response curve, stimulus remaining constant, is modified by the molecular condition of the wire. A wire in a sluggish condition shows feeble response, the recovery being also slow. The same wire after it has been vibrated for a time exhibits a stronger response. Longer time is required for recovery from the action of a stronger stimulus.

Comparison of Electric Excitability of Two Points by the Method of Balance

As already stated, when the clamp is put at the balancing position, alternate equal stimulations of A and B produce equal and opposite electromotive responses, and when the two ends are stimulated simultaneously there is no resultant effect.

Increased Excitability produced by Preliminary Vibration.—If now one-half of the wire, say the A half, be vibrated for a time, the electric excitability of that half will be found to be more or less permanently augmented, presumably by increased molecular mobility conferred by vibration. The response of A would now be found to be greatly enhanced, as compared with its previous response, the response of B remaining the same as before. If now both the ends are simultaneously vibrated, the previous balance will be found to be upset, the resultant showing that A in consequence of previous stimulation, has been rendered the more excitable.

If B be now vibrated for a time, the former approximate balance will be re-established by the enhanced responsiveness of B. Thus the following results are obtained with the clamp at the approximate balancing point :

	Response of A.	Response of B.	Resultant response.
	Divisions.	Divisions.	Divisions.
Approximate balance .	+5	—4·5	+0·5
After the end A has been vibrated.	+10·5	—4·5	+6·0
After the end B has been vibrated for an equal length of time.	+10·5	—9·5	+1·0

Effect of Chemical Reagents.—It will be shown that keeping the electrolyte by which contact is made constant, the electric excitability of the wire depends on the molecular condition of the wire. Certain electrolytes, such as dilute solution of NaCl, dilute solution of bichromate of potash and others, are normal in their action, that is to say, with such contacts the response to stimulation is practically the same as with distilled water contact.

Contact made with dilute NaCl solution may therefore be regarded as the normal contact. There are again certain chemical reagents which enhance the electrical excitability; others on the contrary produce great depression, or abolition of excitability.

Electric Comparator

We may compare the relative electric excitability conferred by chemical reagents by the method of balance. Having previously obtained a balance (with water or dilute NaCl solution at A and B), one contact, say A, is touched with a few drops of very dilute Na_2CO_3, which is an exciting agent. The electric excitability of A will now be found to be greater than that of B as demonstrated by the upsetting of the previous balance, the resultant current being now towards the more excitable A.

	Response of A.	Response of B.	Resultant response.
Both contacts of normal saline.	+12	−12	0
Contact A touched with Na_2CO_3 solution.	+32	−12	+20

Similarly, when A is depressed by a trace of oxalic acid, the electric excitability of A is less than that of B, the resultant deflection being now downwards (current of response towards the relatively more responsive B). It is to be remembered that in all cases *the resultant current of response in the wire is towards the more excitable point.*

An interesting line of investigation rendered possible by a modification of method of balance described above is to compare the relative excitability induced by various chemical reagents, the influence of different strengths of the same reagent, and the modification of the effect by the duration of application. We may thus compare the effect of the reagent in relation to the normal effect of water or dilute NaCl solution. There is again an extremely delicate method of comparison of the relative effects of a series of compounds like Na_2CO_3, K_2CO_3, etc. Balance having been previously obtained between the normal sensitiveness of A and B, the two different solutions are now applied at the two points; the slightest difference in their relative action is at once exhibited by the upsetting of the balance during stimulation, the direction of the resultant deflection indicating the more stimulating reagent.

Resultant Response by Method of Relative Depression or Exaltation

From what has been said, it will be seen that by rendering A and B unequally excitable, a resultant response may be obtained. The block may be abolished, and the wire may be vibrated as a whole; the response will now be due to the differential effect at A and B. For producing difference in excitability we may subject one point, say A, to a preliminary vibration, or apply at the point a suitable chemical reagent. By the application of the latter there will be a small P. D. between A and B, which will simply produce a displacement of the zero. (By means of a potentiometer the galvanometer spot may be brought back to the original position). The displacement of the zero does not affect the general result. The direction of this more or less permanent current, due to the small P. D., gives no indication of the direction of current of response; the direction of the latter is determined by the rule that the responsive current flows towards the more excitable point. The electromotive response induced by mechanical stimulation is algebraically superposed on the existing P. D.

The deflection takes place from the modified zero, to which the spot returns during recovery. I give four records (fig. 72): in (*a*) A is touched with Na_2CO_3 (which is an excitant): a permanent current flows from B to A: response to stimulus is in the same direction as the permanent current (positive variation); in (*b*) A is touched with a trace of oxalic acid (which depresses the excitability), the permanent current is in the same direction as before, but the current of response is in the opposite direction (negative variation); in (*c*) A is touched with dilute KHO (3 parts in 1000), the response is exhibited by a positive variation; in (*d*) A is touched with stronger KHO (3 parts in 100), the response is now exhibited by a negative variation. The last two apparently anomalous results are due to the fact (which will be demonstrated later) that KHO in minute quantities is an excitant, while in larger quantities it is a depressant.

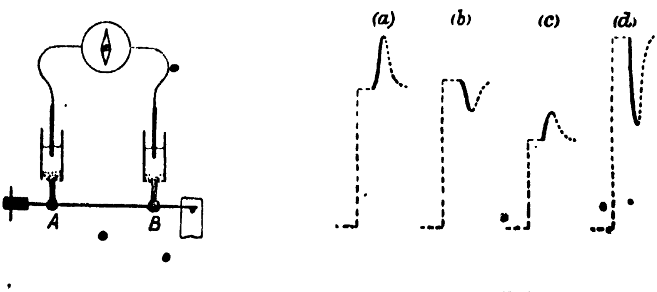


Fig. 72. Response by Method of Relative Depression or Exaltation.

(*a*) Response when A is treated with sodium carbonate—an apparent positive variation.
(*b*) „ „ „ „ oxalic acid—an apparent negative variation.
(*c*) „ „ „ „ very dilute potash—positive variation.
(*d*) „ „ „ „ strong potash—negative variation.

This response is up when A is more excitable and down when B is more excitable.

Lines thus— — — indicate direction of permanent current.

	Permanent current.	Current of response.
A treated with sodium carbonate .	←	←
" " oxalic acid . . .	←	→
" " very dilute potash .	←	←
" " strong potash . .	←	→

Current of response is always towards the more excitable point.

Detection of Minute Physico-chemical Change

I will now describe an experiment which will show in a striking manner how exceedingly delicate is the method of electric response to stimulation, and how by its means we can detect and measure traces of physico-chemical changes in different parts of the same solid. Take a wire and touch two points, one with Na_2CO_3 solution the other with oxalic acid. Wash the wire. There is no trace left of the previous treatment. Let one contact be permanently made at a normal or previously unacted point N. Let the other exploring contact be moved along from the other end towards N, the wire being mechanically stimulated during the test. The galvanometer spot remains quiescent as long as the exploring contact is over normal areas. But as soon as it touches the zone on which is impressed the invisible image of physico-chemical change, the differential effect of stimulus at once reveals it by producing a vigorous movement of the galvanometer spot. At N_1 there was no movement, but there was an upward movement of

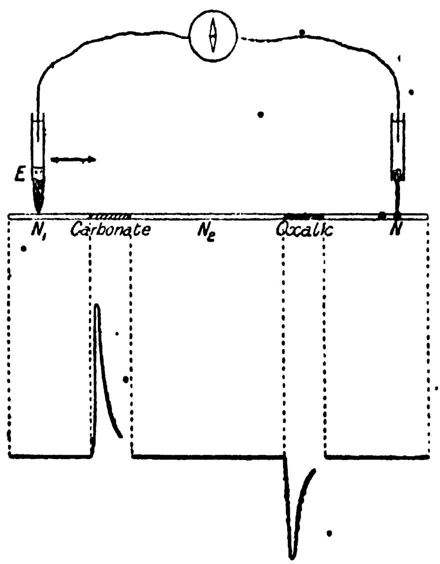


Fig. 73. Electro-molecular Explorer.

response when the explorer came over the stimulated area "Carbonate." As the explorer passed on to N_2 there was a cessation of movement, but when it reached the depressed area marked "Oxalic" there was a vigorous movement downwards (fig. 73).

Interference Effects

I have already described a case of interference in the galvanometric effect when the two points A and B in similar molecular conditions are simultaneously acted on by the same mechanical stimulus. Under these conditions the electric variation at the two points *continuously* balance each other, and there is no resultant effect.

When one point is acted on by a chemical reagent, not only is its electric excitability changed, but its time relations—its latent period, the time-rate of its acquiring the maximum electric variation, and the recovery from the effect of stimulus—become also modified. Using the block method, we may place a drop of excitant Na_2CO_3 on A and depressant KBr on B. On simultaneous vibration of A and B, the A effect being relatively much stronger than B effect, the resultant is an upward deflection. But on moving the balancing clamp away from A (thus decreasing the stimulation intensity of A and increasing that of B) we can find a point where the A effect is equal and opposite to the B effect. But owing to change of time relations, simultaneous vibration of A and B no longer gives a continuous balance; we obtain instead a diphasic variation. The diphasic curve thus obtained is exactly the same as the resultant curve deduced from the algebraic summation of the A and B curves obtained separately.

Continuous Transformation from Positive to Negative through an Intermediate Diphasic Response.—In the following record, fig. 74, I succeeded in obtaining a continuous transformation from positive to negative due to induced changes in the relative sensitiveness of the two contacts. I found that traces of after-effect due to application of Na_2CO_3, even after it is washed off, remain for a time, the increased sensitiveness conferred disappearing gradually. Again, if we apply Na_2CO_3 solution to a fresh point, the sensitiveness *gradually* increases. There is another interesting point, *viz.*, that the beginning of response is earlier when the application of Na_2CO_3 is fresh. In the experiment whose record is given, the wire is held at one end, and successive uniform vibrations imparted to the wire as a whole at intervals of one minute by means of a torsion head at the other end. Owing to after-effect of previous applications of Na_2CO_3, the sensitiveness of A is at the beginning great, hence the resultant response at the commencement is positive or upward. Dilute solution of Na_2CO_3 is next applied to B. The response of B (down) begins earlier, and continues to grow

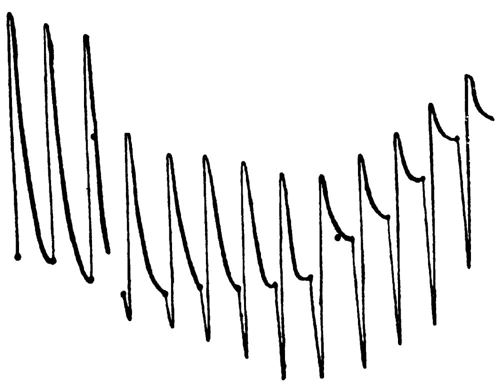


Fig. 74. Transformation from positive to negative through intermediate diphasic variation. Thick dots represent times of application of stimulus.

stronger and stronger. The response therefore shows a preliminary negative twitch of B followed by positive variation of A. The negative grows continuously. At the fifth response, the two components, negative and positive, of the double response become equal; after that, the negative becomes very prominent, the positive dwindling into a feeble and inconspicuous response.

Modification of the Apparatus into "Cell Form"

The series in fig. 75 explains the transformation from the "straight wire" to "cell" form. The wires A and B, cut from the same piece, are clamped separately below; vibration of A (the amplitude of which is measured by a graduated circle) gives rise to a responsive current in one direction; vibration of B produces a current in the opposite direction. Every experiment can thus be verified by corroborative and reversal effects. The intensity of electromotive response varies with the substance, and is sometimes considerable, for example, with "tin," a single vibration may give rise to as high a value as 0·4 volt. The intensity of response does not depend on the chemical activity of the substance, for the electromotive variation in the relatively inactive tin is greater than that in zinc. Again, the sign of response, positive or negative, is sometimes modified by the molecular condition of the wire (see below). In the cell form of apparatus the wires are immersed to a definite depth in the electrolyte; there is thus a perfect and invariable contact between the wire and the electrolyte. The wire is clamped below, and torsional vibration gives rise to a strong electrical response. If the wire be carefully unclamped, vibration is found to cause no electrical response. As all the rest of the circuit is kept absolutely the same in the two different sets of experiments, the results offer conclusive proof that the responsive electromotive variation is solely due to the mechanical stimulation of the acted wire. The excitatory effect due to stimulation persists for a time. This is demonstrated by keeping the galvanometer circuit open during the application of stimulus, and completing it at various short intervals

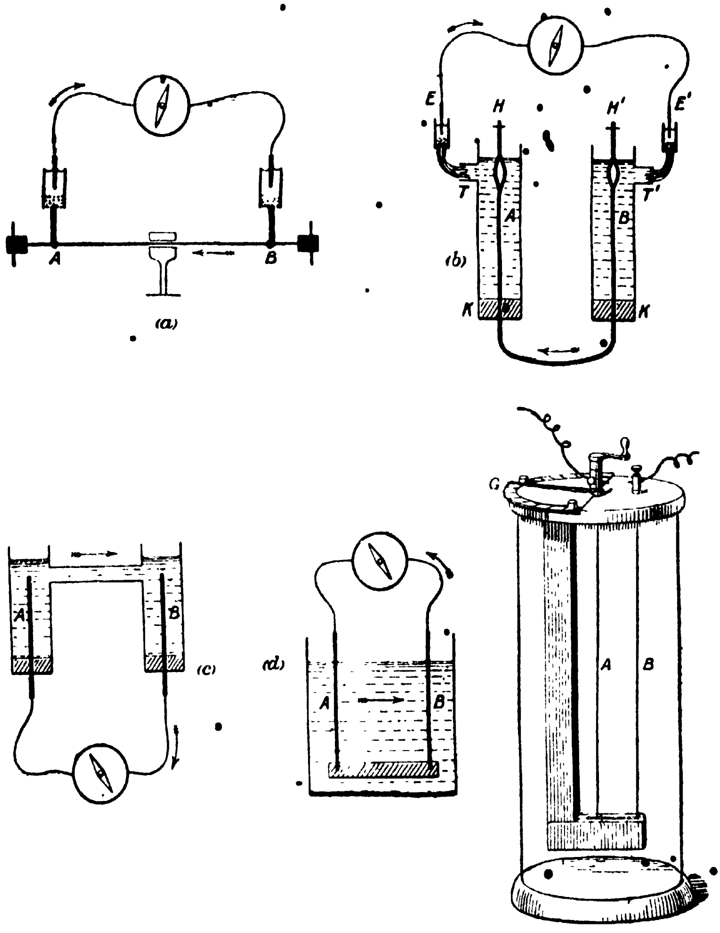


Fig. 75. Successive modifications of the "straight wire" ending in "cell form." (*b*) shows how the ends of A and B of the wire may be vibrated by ebonite clip-holders, H and H'. When A is excited, current of response *in the wire*, normally speaking, is from the unexcited B to the excited A. The stimulated wire becomes zincoid. Note that though the current of response is constant in direction, the galvanometer deflection in (*d*) will be opposite in direction to (*b*). In (*e*) is shown one of the two graduated circles by which the amplitude of vibration is measured.

after its cessation, when a persisting electrical effect diminishing rapidly with time will be observed. When the wire is brought to the normal condition, successive responses to uniform stimuli are exactly similar in the case of metals which, like tin, show no fatigue. I usually interpose a high external resistance, varying from 1 to 5 megohms, so that the galvanometer deflections are proportional to the electromotive variations; the internal resistance of the cell and the variation of that resistance by the addition of chemical reagents are thus rendered quite negligible. Ordinarily tap-water is used as the electrolyte. The responses obtained with tap-water are practically the same as those obtained with distilled water. Zinc wires in $ZnSO_4$ solution give responses similar in character to those given by, for example, Pt or Sn in water.

Character and Intensity of Response dependent on Molecular Condition

The following experiments show how the phenomenon of response is intimately connected with the molecular condition of the acted wire:—

Effect of Annealing.—The photographic records, given in fig. 76, show the equal and opposite responses

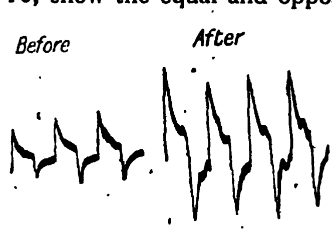


Fig. 76. Series of responses, to uniform stimuli, of both A and B wires, before and after annealing.

in A and B wires to a succession of uniform stimuli. Hot water was now substituted for the cold water (too high a temperature temporarily reduces the response); the cell was then allowed to cool to its old temperature. Records show how the process of annealing had greatly enhanced the amplitude of response.

Effect of Previous Vibration.—The increased sensitiveness conferred by previous vibration has already been referred to before. I give below a record (fig. 77) obtained with platinum; this and similar results obtained

(a) (b) (c)

Fig. 77. Photographic record showing the effect of continuous stimulation in enhancing response (Pt). Each curve shows response (followed by recovery), the stimulus being kept constant throughout. The series of responses (*a*), enhanced to series (*c*) after continuous vibration (*b*).

with other metals clearly show the enhancement of response after preliminary stimulation.

Sometimes the wire gets into a very sluggish condition, when the response almost disappears; in other words, owing to some molecular modification, responsiveness is reduced from the normal positive value (by positive is meant that the acted wire becomes zinc-like or is zincoid) to zero. In these cases annealing or preliminary vibration are usually effective in transforming the sensitiveness from zero to the normal positive value.

Abnormal Response

But the modification of which I have spoken does not stop short of mere abolition of responsive power, but sometimes proceeds further, and actually reverses the sign of response—the excited wire becoming cuproid.

But even in such cases long-continued stimulation transforms the abnormal negative to the normal positive. I give below photographic records which exhibit this. In fig. 78, α, the transformation took place during continued vibration. To detect the point of transformation, I experimented with a platinum cell which exhibited the abnormal effect, and took a long series of records of responses to uniform stimulation acting at

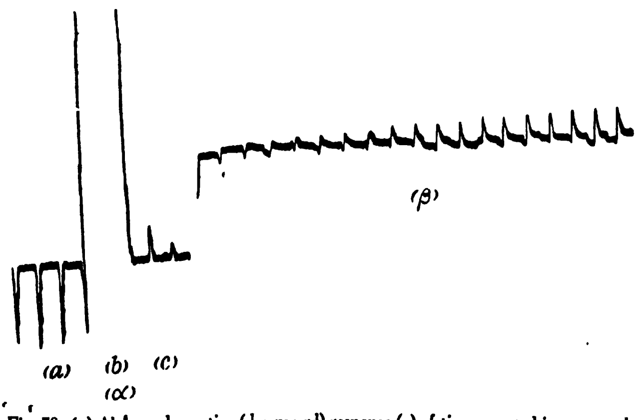


Fig. 78. (α) Abnormal negative (downward) response (a) of tin converted into normal positive (upward) response (c) after continued vibration (b).
(β) Shows points of transition from the abnormal negative to the normal positive (platinum).

intervals of a minute. In the record (fig. 78, β) I have been able to catch the point or rather points of transition.

Abnormal response of animal nerve.—It is interesting to note that similar abnormal response is also exhibited by animal nerve in condition of extreme sub-tonicity. This abnormal response of the nerve is also transformed into normal under continuous stimulation.

Returning to the response of metals we may distinguish the following typical cases. Beginning with the case of extreme molecular modification, we have (1) a condition which gives rise to the abnormal or negative response; after continued vibration the negative becomes less negative, and ultimately becomes converted into positive: (2) an irresponsive or neutral condition; vibration or annealing transforms it into positive: (3) a sluggish, feebly positive, becoming more and more positive after continued vibration: (4) a steady and permanent condition, when the responses are uniform: and lastly (5) when vibration is maintained for too long a time, the positive tends to become less positive, the responses decline—a state of things which is designated as fatigue.

Increased Electromotive Response under increased Intensity of Stimulus

When the intensity of stimulus is increased by increasing the amplitude of vibration, the electric res-

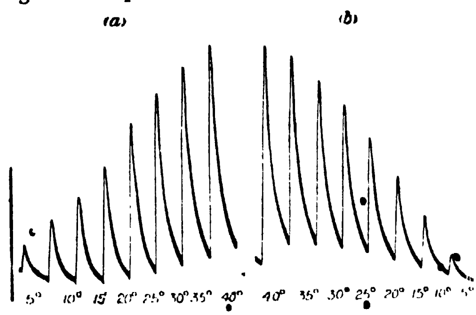


Fig. 79. Photographic records of responses (*a*) from 5° to 40°; (*b*) from 40° back to 5°. The vertical line=0·1 volt.

ponse undergoes an increase. The records given (fig. 79) are for amplitudes of vibration increasing from 5° to 40°, and decreasing from 40° to 5°. The successive stimuli are imparted at intervals of 1 minute. It will be noticed how the responses become enhanced under increasing stimulations.

Table I.—Showing the Increasing Electromotive Response under Increasing Amplitude of Vibration

Vibration amplitude.	Deflection. 23 dns.=0·1 volt.	
	Ascending.	Descending.
5°	5·5	5
10	15	12
20	25·5	26
25	33	32
30	39	39
35	43	43
40	47	48

It will also be noticed that whereas recovery is complete in 1 minute when the vibration amplitude is small, it is not quite complete within that time, when the vibration amplitude is large. Greater strain prolongs the period of recovery. Owing to want of complete recovery, the base line is tilted slightly upwards. This slight displacement does not materially affect the results, provided the shifting is slight. From other records taken through a greater range of stimulation, it appears that in a curve obtained with responsive electromotive variations as ordinates and amplitudes of vibrations as abscissæ, the first part of the curve is, generally speaking, slightly convex to the abscissa. This convexity is more pronounced when feeble stimulation gives rise, as to be presently explained, to a response of opposite sign to that of the normal. The curve is straight in the middle and concave, in the last part where the amplitude of response reaches a limit.

Effect of Sub-minimal Stimulus.—The response is of opposite sign to that of the normal, when the intensity of stimulus is sub-minimal. This characteristic effect I also find in the response of living tissues.

Maximum Effect

If instead of a single vibration of a given amplitude we superpose a rapidly succeeding series, the individual effects are added up and a maximum deflection is produced which remains practically constant as long as the vibration is maintained. A single ineffective stimulus thus becomes effective by the additive effect of several. Too long-continued vibration may cause fatigue, but during half a minute or so, the maximum effect in tin is very definite. For example, a single vibration of 5° gave a deflection of 3·5 divisions; the same when continued at the rate of four times per second gave a maximum deflection of eighteen divisions. A single vibration of 10° of the same wire gave a deflection of 4·5 divisions, but continued vibration gave the definite maximum of 37·5 divisions. I give below a curve (fig. 80) exhibiting the maximum effects for different amplitudes of vibration.

Hysteresis.—Allusion has already been made as to the increased sensitiveness conferred by preliminary vibration. Being desirous of finding out in what manner this is brought about, I took a series of observations for an entire cycle, that is to say, a series of observations were taken for maximum effects, starting from 10° and ending in 100°, and backward from 100° to 10°. Effect of hysteresis is very clearly seen (fig. 80, A); there is a considerable divergence between the forward and return curves, the return curve being higher of the two. On repeating the cycle several times, the divergence becomes much reduced, the wire acquires a more constant sensitiveness.

Effect of Annealing.—I repeated the experiment with the same wire, after pouring hot water and allowing it to cool to the old temperature. It will be seen from the

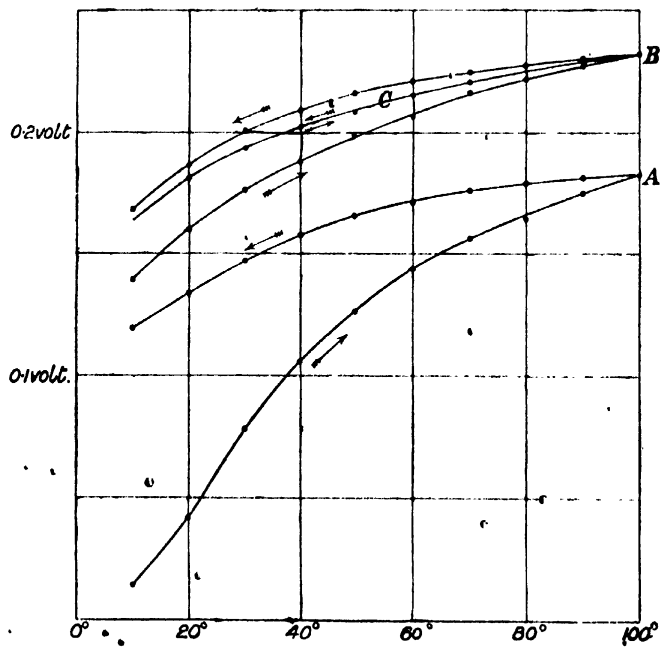


Fig. 80. Cyclic curves for maximum effects due to increasing and decreasing amplitudes of vibration. A, fresh wire; B, after annealing; C, the same after three cycles. Abscissa represents the amplitude of vibration: the ordinate represents the corresponding electromotive variation.

cyclic curve (fig. 80, B), (1) that the sensitiveness has become very much enhanced; (2) that there is relatively less divergence between the forward and return curves. Even this divergence practically disappeared at the third cycle, when the forward and backward curves coincided (fig. 80, C). The above results show in what manner the excitability of the wire is enhanced by purely physical means.

It is very curious to notice that the substitution of dilute Na_2CO_3 solution as electrolyte produces results very similar to that produced by annealing; that is to say, not only is there a great enhancement of sensitiveness, but there is also a reduction of hysteresis. Another curious point is that, whereas with ordinary fresh wire the addition of Na_2CO_3 greatly enhances the sensitiveness, after the wire has been annealed there is comparatively little further increase of sensitiveness due to the addition of the reagent.

Effect of Chemical Reagents

I reproduce photographic records of a few typical cases which will graphically illustrate the influence of chemical reagents. The mode of procedure is as follows. The cell is filled with water, and photographic records are taken of responses to single vibrations of constant amplitude, applied to one of the two wires at intervals of 1 minute. The responses are found to be uniform. Chemical reagents are now added, and responses obtained as before. These exhibit either an increase or a diminution, depending on the exciting or depressing nature of the reagent. It is also quite easy to obtain duplicated results by alternately vibrating the A and B wires. Uniform responses, alternately positive or negative, are first obtained; after the addition of reagent *both* are found to exhibit either an increase or a diminution. As has been said before a very high external resistance, varying from 1 to 5 megohms, is interposed in the external circuit, the slight variation of internal resistance of the cell due to the addition of the reagent being thus rendered quite negligible compared with the total resistance of the circuit. That there is no appreciable variation in the total resistance can be independently verified by applying a known electromotive force before and after the addition of the reagent, when the resulting deflection is found to be the same in the two cases. The deflections are thus simply proportional to the responsive electromotive variations.

Chemical Excitants.—The following record (fig. 81)

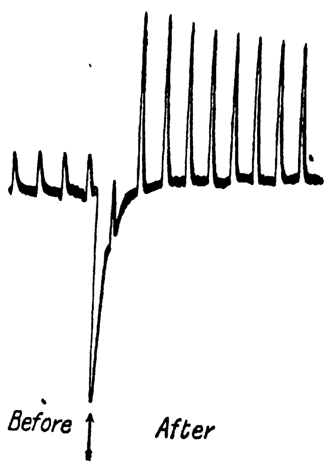
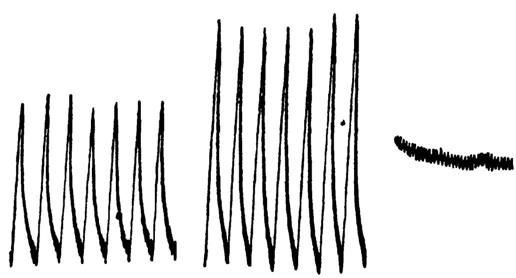


Fig. 81. Enhanced response by the action of Na_2CO_3 solution on platinum. The intensity of stimulus is kept constant throughout. Records to the left show the responses before, and those to the right after, the application of Na_2CO_3.

exhibits the increased response due to the action of Na_2CO_3 on Pt. Another record shows an exactly similar effect on tin. The record of effect was taken two minutes after the application. Other records taken immediately after, show that the enhanced responsiveness takes place gradually with time.

Depressants.—Reagents, like KBr (10 per cent.), produce a depression in the response. There are again others which abolish the response almost completely, for example, 3 per cent. KHO solution (fig. 82, c). One of the most effective reagents which abolishes the response is oxalic acid. The depressing effect of this reagent is so great that a strength of 1 part in 10,000 is often sufficient to produce an abolition of response.*



(a) (b) (c)

Fig. 82. Records showing the opposite effects of weak and strong solutions. (*a*) Normal response ; (*b*) increased response due to addition of 0·3 per cent. KHO ; (*c*) abolition of response by 3 per cent. KHO.

* The various phenomena connected with the response in inorganic substances—the negative variation—the relation between stimulus and response—the increased response after continuous stimulation—the abnormal response converted into normal after long-continued stimulation—the diphasic variation—the increase of response by stimulants, decrease by depressors, and abolition by "poisons," so-called—all these are curiously like the various response phenomena in living tissues. A complete account of the mutual relation between the two classes of phenomena will be found in my work "The Response in the Living and Non-living."

Opposite Effects of strong and feeble dose.—The most curious effect is that exhibited by the same reagent when the strength of solution is varied. This is clearly seen in record (fig. 82), in which (*a*) gives the normal response in water; (*b*) shows the enhancement of response by a highly dilute solution of KHO, 3 parts in a thousand. The response was completely abolished by a stronger solution, 3 parts in a hundred (fig. 82 *c*).

Effect of "poisons."—Certain agents like oxalic acid cause a total abolition of response, like the action of poisons on living tissues.

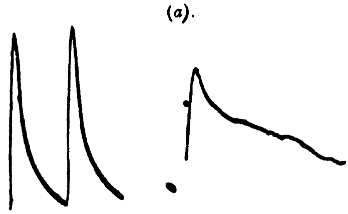
The facts described above appear to show that the enhancement or depression of response may, at least to a considerable extent, be due to the increase or diminution of molecular mobility. With a given stimulus, the height of response and the form of the response curve is determined by the element of molecular friction. In connection with this, it is instructive to observe the records of vibrations of a torsional pendulum, the friction being gradually increased by immersing the pendulum in a viscous fluid. The various types of response-curves in metals are found to be very similar to the above.

Of these I give an interesting example. With moderate friction the successive curves obtained with the pendulum are like those given in the left of fig. 83 (*a*). With increased friction the height of the curve is diminished, the maximum is reached later, and the recovery becomes much prolonged like the curve to the right. With still greater friction there is an arrest of recovery.

It would appear as if the reagents which abolish response in metals produce a similar molecular arrest.

The following photographic records seem to lend support to this view. If the oxalic acid be applied in large

(a).



(b).

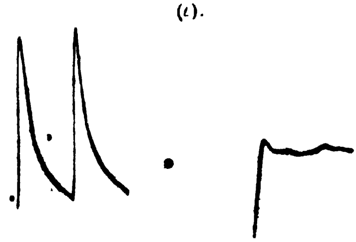


Fig. 83. Photographic records showing the effect of " molecular arrest." The two curves to the left of each set show the normal response; curve to the right in (a) shows partial and in (b) complete arrest.

quantities, the abolition of response is complete; but on carefully applying just the proper amount, I find that the stimulus evokes a responsive electric variation which is less than the normal, and the period of recovery is very much prolonged from the normal 1 minute before to 5 minutes after the application of the reagent. In the lower record (fig. 83) the normal response and recovery is seen in the left record. After the application of oxalic acid the record to the right shows a pronounced arrest, *i.e.*, there is now no recovery. Note also that the maximum is attained much later. Stimuli applied after the arrest produce no effect, as if the molecular mechanism had become locked up.

Conclusion

1. Molecular disturbance produced by mechanical stimulation gives rise to an electromotive response. In the majority of cases, under normal conditions, the responsive electrical current in a wire is from the less to the more stimulated.

2. Response may be obtained by (1) method of block, (2) by methods of negative or positive variation.

3. The electromotive response disappears on the cessation of stimulus.

4. The intensity of the electrical response is modified by the molecular condition of the wire. Annealing, or previous stimulation enhances the electric response.

5. Abnormal response due to molecular modification is transformed into normal by previous stimulation.

6. The intensity of electric response is increased with increasing intensity of stimulation.

7. In a curve showing the relation between intensity of stimulus and resulting response, the first part is slightly convex to the abscissa, the second is approximately straight, and the third concave. The response tends to reach a limit.

8. Minimally effective stimulus becomes effective by summation of stimuli. A maximum effect is produced, determined by the intensity of individual stimulation.

9. Hysteresis is exhibited in cyclic curves. The forward and return curves tend to coincide after several cycles. Previous annealing reduces hysteresis, and after one or two cycles the wire assumes a constant sensitivity.

10. Chemical reagents may profoundly modify the electric excitability. Some of them increase the excitability, while others depress or abolish it.

11. The effect of a feeble dose is often opposite to that of a stronger dose.

12. By touching different points of the same wire with different reagents, the excitability of these portions are rendered unequal. Hence a responsive electromotive variation is obtained by stimulating the wire as a whole. The current in the wire is from the less to the more excitable.

13. This method enables the detection of invisible traces of physico-chemical change in a wire.

14. Chemical reagents not only change the excitability but also the quickness of response. Two points having two different rates thus give diphasic and other interference effects.

(*Proc. Roy. Soc. May* 1902.)

XXI

ELECTRIC RESPONSE IN ORDINARY PLANTS UNDER MECHANICAL STIMULATION

Discovery of the similarity of response in inorganic substances and in animal tissues led me to the investigation of responsive phenomena in the intermediate region of life of plants.

The action of stimulus on living substances is usually detected by two different methods. In the case of motile organs, stimulus causes a change of form. Mechanical response may thus be obtained in a contractile tissue such as a muscle. But in others, nerve for example, stimulus causes no visible change; the excitation of the tissue may, however, be detected by characteristic electromotive changes. The advantage of the electric mode of detection of response is its universal applicability. In cases where mechanical response is available, as in the muscle, it is found that records of mechanical and electrical responses are very similar to each other.

The intensity of electrical response in animal tissue is modified by the physiological activity of the tissue. When this activity is in any way depressed, the intensity of electrical response is also correspondingly diminished. When the tissue is killed, the electrical response disappears altogether.

Burdon Sanderson, Munck, and others found electric response to occur only in sensitive plants. I wished to find out whether the responsive electric variation was confined merely to organs of plants which exhibit such remarkable mechanical movements, or whether it was a universal phenomenon characteristic of all plants and of all their different organs. My attempt was moreover directed in determining throughout the whole range of response phenomena a parallelism between the animal and the vegetable. That is to say, I desired to know, with regard to plants, what was the relation between the stimulus and response; what were the effects of superposition of stimuli; whether fatigue was present, and in what manner it affected the response; what were the effects of extremes of temperature; whether chemical reagents exercised any influence on the plant-response, as anæsthetics and poisonous drugs affected the responses of nerve and muscle.

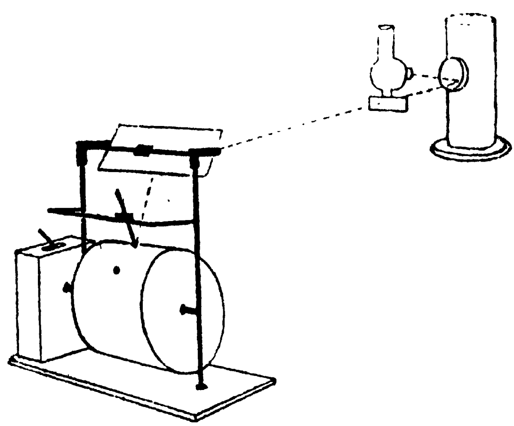


Fig. 84. Response Recorder.

Experimental Arrangements

The galvanometer used is a sensitive dead-beat D'Arsonval. A current $1/10^9$ ampere gave a deflection of 1 mm. at a distance of 1 metre.

The Response Recorder.—In these response-curves the ordinate represents the intensity of E. M. variation, and the abscissa the time. The curves are obtained directly, by tracing the excursion of the galvanometer spot of light on a revolving drum. The drum, on which is wrapped the paper for receiving the record, is driven by clockwork (fig. 84). Different speeds of revolution can be given to it by adjustment of the clock-governor, or by changing the size of the driving-wheel. The galvanometer spot is thrown down on the drum by an inclined mirror. A stylographic pen attached to a carrier rests on the writing surface. The carrier slides over a rod parallel to the drum. On stimulation, the resulting excursion of the spot of light is followed by moving the carrier which holds the pen; after the cessation of stimulus the excitatory effect slowly disappears, and the galvanometer spot returns gradually to its original position. The response and recovery are thus directly traced on the recording surface. We can calibrate the value of the deflection by applying a known electromotive force and noting the deflection which results. The speed of the clock is previously adjusted so that the recording surface moves exactly through, say, one inch a minute; this speed can, however, be increased to suit any particular experiment. Very accurate records can thus be obtained in a very simple manner. A large number of records might be taken by this means in a comparatively short time.

Photographic Recorder.—The records may also be made photographically. A clockwork arrangement moves a photographic plate at a known uniform rate, and a curve is traced on the plate by the moving galvanometer spot of light. The records given in this paper are accurate reproductions of those obtained by one of these two methods.

Graduation of the Intensity of Stimulus

The important conditions for securing quantitative results are (1) the maintenance of uniform intensity of stimulation in certain experiments and (2) the graduated increase of intensity in others.

Stimulus of torsional vibration.—I find that torsional vibration affords a very effective method of stimulation. The plant-stalk may be fixed at one end, the other end being held in a tube provided with clamping jaws. A rapid torsional to-and-fro vibration can now be imparted to the stalk by means of the handle H. The amplitude of vibration, which determines the intensity of stimulus, can be accurately measured by means of a graduated circle. The plant chamber and the vibrational stimulator is shown in fig. 85.

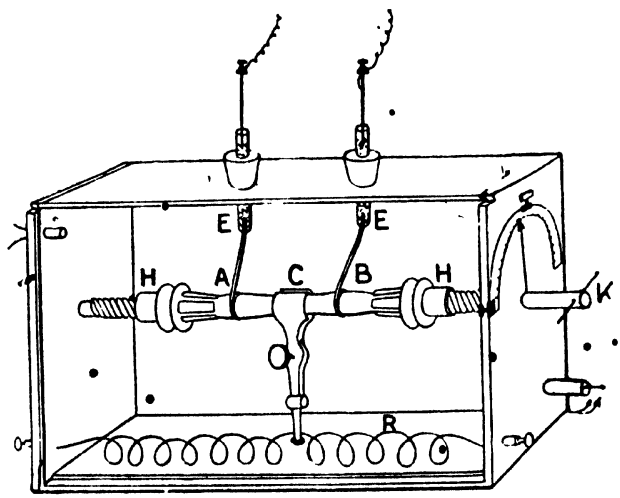


Fig. 85. The plant chamber. Amplitude of vibration which determines the intensity of stimulus is measured by the graduated circle seen to the right. The glass chamber is air-tight. The plant is clamped in the middle by C which acts as a block. Temperature is regulated by the electric heating-coil R. For experiments on anæsthetics, vapour of chloroform is blown in through the side tube.

Intensity of Stimulus dependent on Amplitude of Vibration

A block is produced by clamping the plant in the middle at C; increased stimulation is found to occur in the tissue by increased amplitude of vibration.

The Physiological Character of Response

I now proceed to demonstrate that the response given by the plant is physiological and that it affords an accurate index of the vital activity of the plant. For it will be found that whatever tends to exalt or depress this activity also tends to increase or diminish the intensity of electric response.

The test applied by physiologists, in order to discriminate as to the physiological nature of the response consists in observing the effects of anæsthetics, poisons, and exceedingly high temperatures, all of which are known to depress or destroy the activity of life.

Effect of Anaesthetics and Poisons.—I took 30 leaf-stalks of horse-chestnut, and divided them into 3 batches, of 10 each. One batch was kept in water, to serve as control experiment, another in chloroform water, and the third in a 5 per cent. solution of mercuric chloride.

Average response of stalks kept in water=23 divisions.

Average response of stalks kept in chloroform= 1 division.

The response of stalks kept in poisonous mercuric chloride was completely abolished.

Effect of High Temperature.—A leaf-stalk is taken, and using the block method strong responses are obtained at both ends A and B. The stalk is now immersed for a short time in water at 60° C. After this treatment the responses are found to be completely abolished. As all the external conditions were the same in the two series of experiment, the only difference being that in one the stalk was alive, and in the other killed, we have here a further and conclusive proof of the physiological character of electric response in plants.

The same facts may be demonstrated in a still more striking manner by first obtaining two similar but opposite responses in a fresh stalk at A and B, and then killing one half, say B, by immersing that half in hot water. The stalk is replaced in the apparatus; repetition of the experiment shows that whereas the A half gives strong response, the end B gives none.

Uniform Responses

Uniform responses may be obtained with certain plants in a vigorous condition, and when sufficient period of rest is allowed for complete recovery. The record given below shows the remarkable uniformity of response given by radish. The response of plant is by the induced galvanometric negativity of the excited tissue just as in the tissue of the animal.

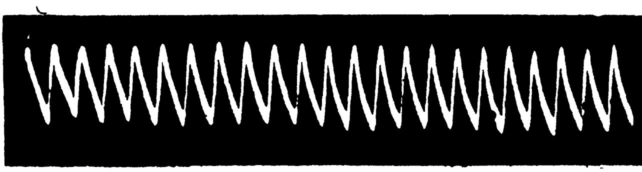


Fig. 86. Uniform responses (Radish).

Fatigue

The responses however exhibit fatigue by shortening the intervening period of rest. The first four responses in fig. 87 show that there is a complete recovery of the tissue one minute after the application of the stimulus.

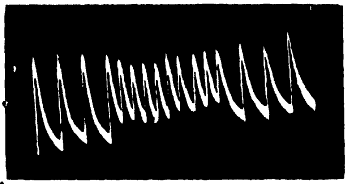


Fig. 87. Appearance of fatigue in plant under shortened period of rest.

The molecular condition is exactly the same at the end of the recovery as at the beginning of stimulation; the second and succeeding response-curves therefore are exactly similar to the first, *provided sufficient interval in each case has been allowed for complete recovery.*

The rhythm was next changed and stimuli of the same intensity as before applied at intervals of half a minute, instead of one. It will be noticed that these responses in the second part appear much feebler than those in the first set, in spite of the equality of stimulus. The original rhythm of one minute was now restored and the succeeding curves at once show restoration of the original amplitude of response.

Increased Response under increasing Stimulus

I will now show that the electric response is not merely a qualitative phenomenon, but that increased intensity of stimulus always gives rise to a definite increase in the amplitude of response.

In order to obtain the simplest type of effects, not complicated by secondary phenomena, it is necessary to choose specimens which exhibit little fatigue. Having obtained such a specimen I took records of responses for increasing stimuli caused by increasing amplitudes of vibration.

In the record given (fig. 88) the amplitude of vibration was increased from 2°·5 to 12°·5 by steps of 2°·5

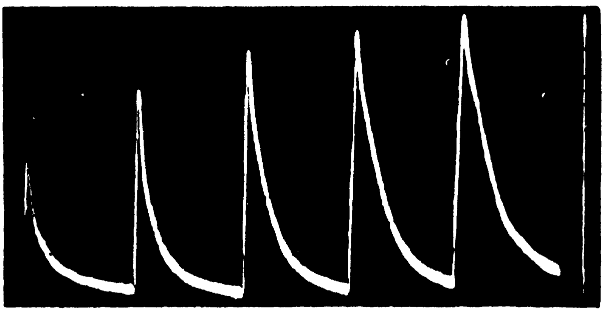


Fig. 88. Increasing responses to increasing vibrational stimuli; the vertical line to the right represents ·1 volt.

(cauliflower-stalk). It will be noticed the remarkably definite manner in which the response increases with the stimulus. The rise is at first rapid, but with high intensities of stimulus there is a tendency for the response to approach a limit.

Superposition of Stimuli

Additive effect.—There is apparently little or no response when the stimulus is feeble. But even a sub-minimal stimulus, though singly ineffective, becomes effective by the summation of several. This is shown in fig. 89, where the first record *a* is the response to a feeble stimulus, and the second *b* is the response to the same stimulus repeated in quick succession, thirty times.

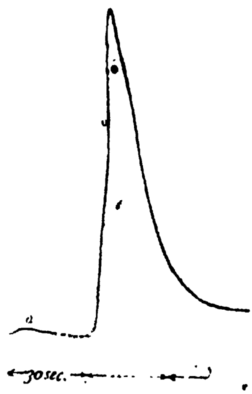


Fig. 89. Additive effect of singly ineffective stimuli in plant.

Effect of Steam

The plant was mounted in a chamber into which steam could be introduced. I had chosen a specimen which gave regular responses. On the introduction of

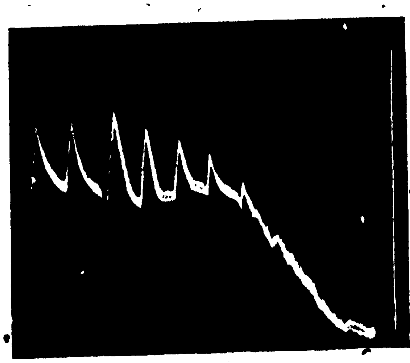


Fig. 90. Effect of steam in abolishing response with death of plant. The two records to the left give responses at 20° C., after which steam was introduced.

steam, with consequent rise of temperature, there was a transitory augmentation of excitability. But this quickly disappeared, and in five minutes the response disappeared with the death of the plant (fig. 90).

Effects of Anaesthetics and Poisons

The most important test by which vital phenomena are differentiated is the influence of narcotics and poisons on response. I have already shown how plants which previously gave strong response, did not, after application of an anæsthetic or poison, give any response at all. In those cases it was the last stage only that could be observed. But it appeared important to be able to trace the growing effect of anæsthetisation or poisoning throughout the process.

Effect of Chloroform.—The mode of experiment was (1) to obtain a series of normal responses to uniform stimuli, applied at regular intervals of time, say one minute, the record being taken the while on a photographic plate. (2) Without interrupting this procedure, the anæsthetic agent, chloroform vapour, was

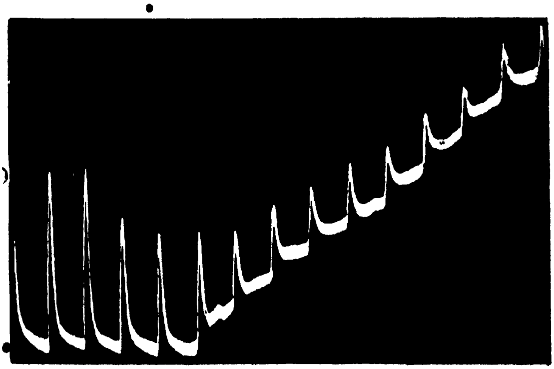


Fig. 91. Effect of chloroform.

blown into the closed chamber containing the plant. It will be seen how rapidly chloroform produced depression of response which afterwards culminated with death and abolition of response (fig. 91).

Exactly similar effects were obtained with chloral, also with formalin. These were applied in the form of solution on the tissue at the two leading contacts.

It has been shown that the electric response is a faithful index of physiological action and that such a response is given by all plants and by their different organs. It has also been shown that in the matters of response by induced galvanometric negativity, of modification of response by high and low temperatures, they are strictly correspondent to similar phenomena in muscle and nerve. Judged by the final criterion of the effect produced by anæsthetics and poisons, these electric responses in plants fulfil with animal tissues the test of vital phenomenon.

The electro-physiological investigation on plants will undoubtedly throw much light on the response phenomena in the animal. With animal tissues, experiments have to be carried on under many great and unavoidable difficulties. The isolated tissue, for example, is subject to unknown changes inseparable from the approach of death. Plants, however, offer a great advantage in this respect, for they maintain their vitality unimpaired during a very great length of time. In animal tissues, again, the vital conditions themselves are highly complex. The essential factors which modify response can, therefore, be better determined under the simpler conditions which obtain in plant life.

(*Journal Linn. Soc., Vol. XXXV,* 1902.)

XXII

THE QUADRANT METHOD OF RESPONSE TO STIMULUS OF LIGHT

In addition to the method of electromotive variation, I succeeded in perfecting an independent means for recording the response of plants by the variation of its electric resistance. The living tissue excited by any mode of stimulation—mechanical, electrical or photic—responds by a diminution of resistance. A new method of resistivity variation of extreme delicacy will now be described by which the response of the leaf to the stimulus of light can be recorded.

The principle of the method will be understood from the diagram given at the lower end of figure 92, which represents a leaf blade of *Tropaeolum* in which its four quadrants P, Q, R, S, serve as the four arms of a Wheatstone Bridge. The diagonal connections are made with the battery and the galvanometer respectively. The three contacts with the leaf may be fixed, and the fourth moved slightly to the right or to the left till an exact balance is obtained in darkness, when PQ=RS. One of the pairs of opposite quadrants P and Q is shaded by a double V-shaped screen. Exposure of the leaf to light produces a variation of resistance not of one, but of two opposite arms of the bridge R and S; the upsetting of the balance is thus due to the *product* of the variations of resistance in the two opposite quadrants. The responsive galvanometer deflection is found to be very large indicating a diminution of resistance in the quadrants stimulated by light. The double V-shaped screen is next turned through 90°; the quadrants P and Q are now exposed to light, and R and S shaded

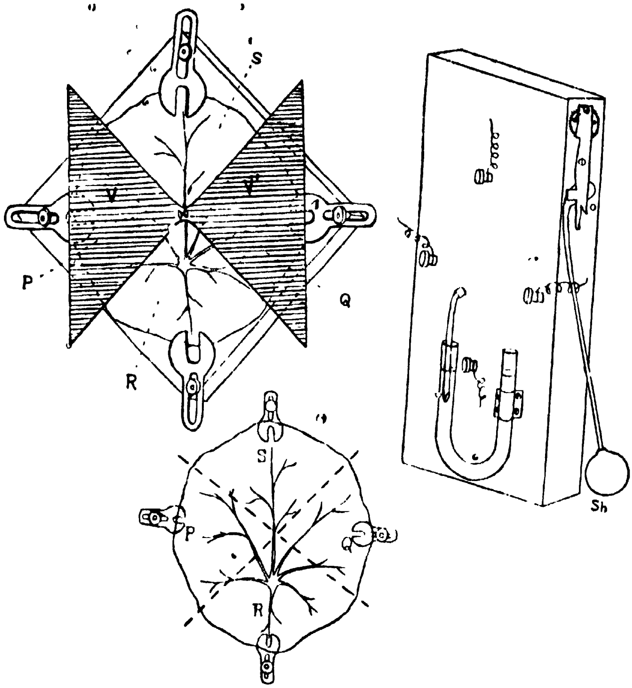


Fig. 92. The Quadrant Method of response by variation of electric resistance. Two opposite quadrants of the leaf are shaded. Electric connections are made at the *junctions* of the quadrants and not at the middle as shown in figure.

from it. The resulting upset of the balance and the galvanometer deflection is now in an opposite direction.

The reliability and the sensitiveness of the Quadrant Method may thus be tested by obtaining equal and opposite responses under alternate illumination of the two pairs of quadrants; the test in confirmation of the above will be found in records given in figure 93.

After securing exact balance, the double V-shaped screen is kept fixed, and the leaf mounted in a rectan-

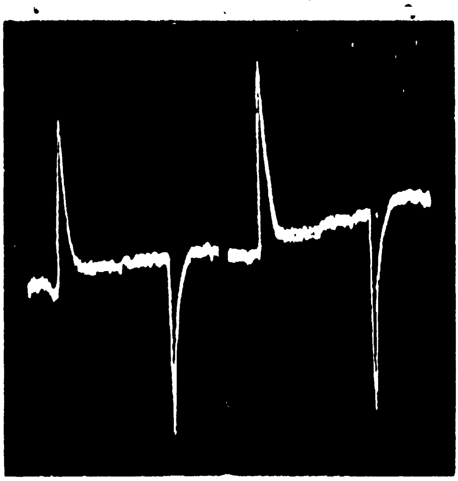


Fig. 93. Equal responses in opposite directions by alternate illumination of the two pairs of quadrants.

gular dark chamber closed except at the front, which carries a photographic shutter by which one pair of quadrants is exposed to light for a definite duration. The electric connections with the leaf are led to four binding screws; the petiole protruding from the box is dipped in an U-tube filled with water (*cf.*, right-hand illustration of fig. 92).

The source of light is an arc or an incandescent lamp, placed inside a lantern, the condenser of which sends a parallel beam of light. A rectangular glass trough filled with alum solution is interposed in the path of light to absorb the heat rays. The duration of exposure is varied according to the sensitiveness of the specimen; the usual period of exposure is about 20 seconds.

RESPONSE TO LIGHT FROM A SINGLE SPARK

The extreme sensitiveness of the quadrant method is demonstrated by the record given in figure 94.

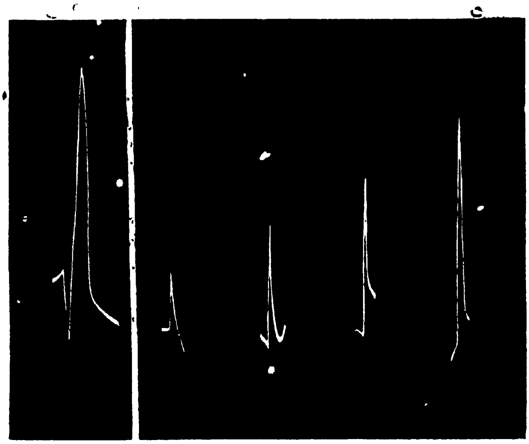


Fig. 94. Fig. 95.

Fig. 94. Response to light from a single spark.
Fig. 95. Effect of stimulus of light increasing in the ratio of 1 : 3 : 5 : 7.

The duration of a spark-discharge of a Leyden Jar may be regarded as of the order of hundred thousandth part of a second. The discharge took place at a distance of 15 cm. from the leaf and the response is seen to consist of a preliminary positive twitch followed by a large negative response, indicative of normal diminution of resistance. The leaf exhibited a complete recovery.

Effect of increasing Intensity of Light

The arc lamp is taken out of the lantern, and the diverging beam employed for the following experiment. As the intensity of light varies as the square of the distance, suitable marks were made on the scale fixed on the table, so that the intensity of light incident on the leaf was increased in the proportion of 1 : 3 : 5 : 7 by bringing the arc nearer the leaf at the particular distances marked on the scale. The duration of exposure was kept the same.

The responses under increasing intensities of light are seen in figure 95. The resistance is seen to undergo a diminution with the increasing intensity of stimulus.

Effects of Stimulants and Depressants

The responses are appropriately modified by stimulating or depressing agents. Dilute vapour of ether, for example, increases the excitability and enhances the amplitude of response. Strong dose of chloroform, on the other hand, causes depression and death as indicated by gradual diminution and final abolition of response.

The results of other investigations, fully described elsewhere, show that external stimulation gives rise to two definite protoplasmic reactions, which may be described as the A- and the D-effects. The A-effect, usually induced by sub-minimal stimulus, finds outward expression, by induced expansion, increase of turgor, enhancement of the rate of growth, galvanometric positivity and increase of electrical resistance. The D-effect (predominantly induced under stimulus of moderately strong intensity) is outwardly manifested, on the other hand, by contraction, diminution of turgor, diminished rate of growth, galvanometric negativity and diminution of electric resistance. Under very strong stimulation the response tends to become multiple. The following table shows the parallel effects exhibited by diverse modes of response.

Table showing parallelism in different modes of response

External change	Mechanical response	Variation of growth	Electro-motive response	Resistivity variation
Sub-minimal stimulus	Expansion; eroctile response	Accelera-tion of growth	Galvano-metric positivity	Increase of resistance
Moderate stimulus	Contrac-tion and fall of leaf	Retarda-tion of growth	Galvano-metric negativity	Diminu-tion of resistance
Strong stimulus	Multiple response	Multiple response	Multiple response	Multiple response
Depressants	Diminished response	Retardation of growth	Diminished response	Diminished response
Stimulat-ing agents	Enhanced response	Accelera-tion of growth	Enhanced response	Enhanced response

(*Life Movements in Plants, Vol. IV*, 1923.)

XXIII

ON A VEGETABLE PHOTO-ELECTRIC CELL

When light is incident on the sensitive pulvinus of *Mimosa pudica*, the response is by contraction and the resulting fall of the leaf. A diminution of electric resistance of tissues of plants under stimulation has also been demonstrated in the previous paper. The electromotive response of *galvanometric negativity*, under the excitatory action of light, has previously been demonstrated in my work on *Comparative Electro-physiology*. I here describe a new and interesting method for this demonstration.

Normal Response to Light

For obtaining the normal response, we take a vigorous leaf and pin it on a paraffined block of wood. Two pieces of thin muslin in connection with non-polarisable electrodes are spread over two areas of the leaf A and B; when these pieces of muslin are moistened with normal saline, they become practically transparent. When light from an arc lamp is thrown on A, that area becomes galvanometrically negative and the responsive current flows in the direction GAB. Light thrown on B (A being shaded) causes a response in the opposite direction, (left illustration fig. 96).

The fact, that the electromotive response under light is the same as that under a different mode of stimulation such as mechanical, is demonstrated as follows. The moist piece of cloth on A is rubbed against the surface of the leaf by means of a glass rod; or the surface is struck with a glass hammer. In both these cases, A end of the leaf becomes galvanometrically negative, the direction of the current of response being the same as when A is stimulated by light.

Having given a simple demonstration of the fundamental reaction, I describe the photo-electric cell made of two pieces of leaf. In the experiment just described, the resistance of the circuit is very great, on account of the high resistance of the two non-polarisable electrodes, and the resistance offered by the leaf. The non-polarisable electrode, moreover, is a source of trouble; an attempt was therefore made to discard it, and employ other means for diminishing the resistance of the circuit. For the following experiments we employ the leaf of *Musa sapientum* which is divided into two longitudinal halves by a slit along the thick midrib. Two pieces of leaves are thus obtained about 10×10 cm. which are hung parallel and separated from each other in a rectangular glass vessel filled with normal saline; the distance between the two leaves is 3 cm. Two gold wires are thrust through the length of the two divided midribs; they serve as external electrodes of the photo-voltaic cell, which lead to the galvanometer G. The glass trough is placed inside a rectangular wooden chamber with two hinged doors on opposite sides, by which the leaf A or B could be alternately exposed to light (fig. 96). When the doors are closed, A and B are in darkness; they are practically iso-electric, there being no current in the galvanometer. But exposure of A to light gives rise to a difference of potential between A and B, A becoming galvanometrically negative, the resulting deflection being in one direction. Exposure of B gives rise to a responsive deflection in the opposite direction. The two leaves serve as the two plates in a voltaic cell; but unlike ordinary voltaic cell with elements of different metals,

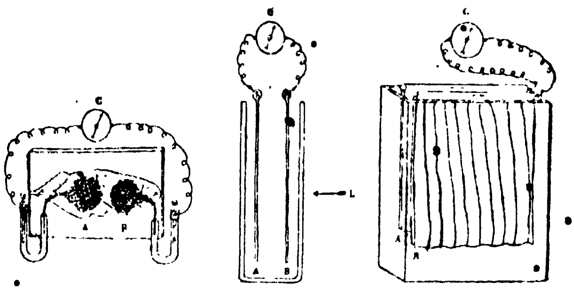


Fig. 96. Diagrammatic representation of a vegetable photo-electric cell. The first illustration shows electric connections with two portions of the leaf A, B, by non-polarisable electrodes. The second and third illustrate side and front views of the photo-voltaic cell made of two half-leaves.

the two plates of the vegetable cell are made of two halves of the same leaf, the electromotive force being generated by the excitatory action of light on one of the two half leaves. The advantages of this method of obtaining electromotive response are: (1) that the troublesome employment of the non-polarisable electrodes with their high resistance is dispensed with; (2) that the area of the surface of the leaf exposed to light is considerably increased; (3) that the electric resistance of the circuit is greatly decreased, since the interposed resistance is that of normal saline about 3 cm. thick with a broad section of 100 square cm.; and (4) that alternate and opposite responses may be obtained by successive exposures of the two leaf-plates to the parallel beam of an arc lamp, this being easily secured by turning the rectangular plant chamber round a revolving base.

Response of the Leaf to Light

The photo-voltaic cell thus constructed is stimulated by light from an arc lamp which passes through a trough of alum solution for absorption of the heat rays. Successive exposures are made for 10 seconds and records obtained on a moving photographic plate. The normal responses are uniform, exhibiting induced galvanometric negativity as seen in the up-curves. On the cessation of light there is a complete recovery; the recovery shows in fact, an overshooting towards galvanometric positivity from which it returns almost to the original zero position before stimulation (fig. 97). The records indicate the existence of dual reactions, a negative variation or D-effect followed by a positive variation or the A-effect.

Positive Response to Light

Some observers have obtained with green leaves a response of galvanometric positivity. The results of following investigation offer an explanation of the apparent anomaly. I have shown elsewhere that a positive response occurs under a stimulus below the critical intensity, and that this critical point is low in highly excitable tissues, whereas it is relatively high in others which are less excitable. The excitability, I find, is modified by the age and vigour of the specimen. It is very considerable at moderately young age, being feeble when the tissue is either very young or very old. The same stimulus which evokes a negative response in a vigorous middle-aged leaf may, therefore, be expected to give rise to a positive response in a very young leaf or in a leaf which is becoming yellow with age.

The above anticipations have been found verified in the following experiments. In figure 98 is seen the positive response of a very young leaf of Musa; the next figure shows similar positive response given by a

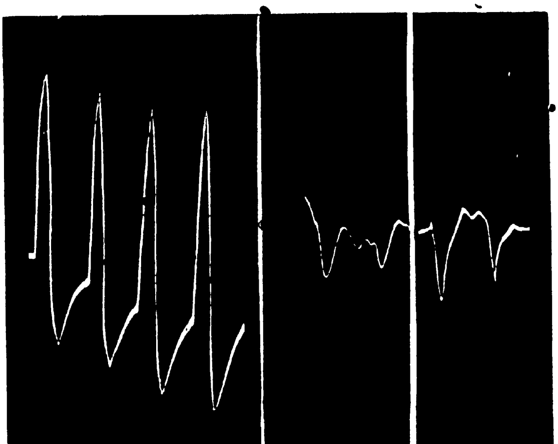


Fig. 97. Fig. 98. Fig. 99.

Fig. 97. Normal electromotive response in a vigorous specimen. Note the transient positive after-effect.

Figs. 98 and 99. Abnormal positive response in a very young and in a very old specimen.

very old leaf. There is an additional factor, to be presently described, which also tends to induce a positive response.

Effect of Increasing Duration of Exposure

The reaction under light, is within limits, proportional to the quantity of light, that is to say, on intensity of light multiplied by duration. The effect of increasing intensity of light has already been shown (cf. fig. 95). When the intensity is maintained constant, the amplitude of response undergoes an increase with the increased duration of exposure (fig. 100). But this increase does not go on indefinitely, for the continuous action of light causes a maximum negative response beyond which a decline sets in. It is probable that this is due to an opposing element which tends to neutralise the normal excitatory D-effect. The existence of this opposing A-reaction has already been seen in the transient after-effect in figure 97. Other results which I obtained, show that stimulus induces, in general, both the D- and A-effects; in excitable specimens the D-effect is predominant and therefore, masks the A-effect; the positive A-effect is, however, exhibited under feeble or even as an after-effect of strong stimulation.

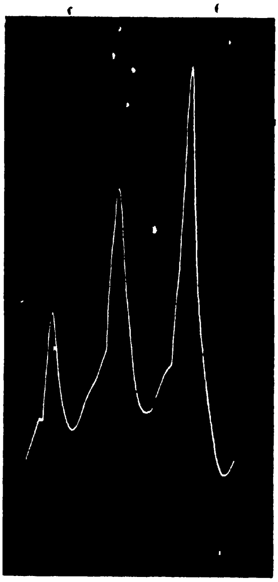


Fig. 100. Effect of increasing durations of exposure of 5, 10 and 15 seconds.

Certain conditions, moreover, are specially favourable for the exhibition of the A-effect. When the green leaf has an abundant supply of chlorophyll, the photo-synthetic process of building up becomes specially marked. I have thus obtained under the action of light, a positive response with the green leaf of *Luctuca* *sativa* in which chlorophyll is present in great abundance.

The fact that positive response is associated with assimilation is proved by my experiments on photo-electric response of water plants. This building up process by photosynthesis is here independently demonstrated by profuse evolution of oxygen. These aquatic plants exhibit marked positive electric response during strong illumination, recovery taking place on the cessation of light (fig. 101).

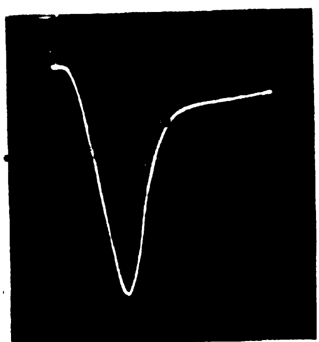


Fig. 101. The positive electric response of Hydrilla.

Effect of Continued Action of Light

The positive element in the response may be indirectly demonstrated even in the normal *Musa* leaf. In figure 102 is seen the effect of continuous action of light which at first exhibits the predominant negative attaining a maximum ; the positive element now begins to increase with the duration of light and causes a reversal ; at a certain stage, the two elements, D and A, balance each other, the resulting response becoming horizontal, On the stoppage of light, the antagonistic A element ceases to be active, while D appears to be persistent. The result is a sudden unmasking of the negative, hitherto held in balance during exposure to light. A negative response with subsequent recovery thus occurs on the cessation of light.

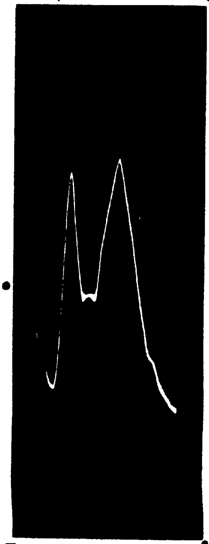


Fig. 102. After-effect of light. The maximum negative is opposed by growing positive and the balance attained is seen in the horizontal portion of the curve. Stoppage of light causes the unmasking of the negative followed by recovery.

The responses of *Musa* and of actively assimilating *Hydrilla* are seen to exhibit characteristic differences on account of the relative predominance of the D- or A-effect. In *Musa*, D is predominant, A being exhibited either as a positive after-effect or by the overshooting of response in the positive direction. In an actively assimilating *Hydrilla* plant, on the other hand, A is predominant and the response is positive. In less vigorous *Hydrilla* the positive becomes masked by the negative, when the resultant response appears to be similar to that of *Musa*.

(*Life Movements in Plants, Vol. IV*, 1923.)

XXIV

THE PHOTOSYNTHETIC RECORDER

The incessant activities of life require expenditure of energy that has been previously stored by the organism. Taking, for example, the rise of sap, the ceaseless pumping activity of certain propulsive tissue raises enormous quantities of water to a considerable height. The energy of doing this work resides in the breakdown of complex chemical substances in internal combustion or respiration. The loss of energy must be restored by absorption and storage of energy from outside.

This is secured in green plants by photosynthesis, carbon being fixed for nutrition of the plant with the help of sunlight.

The carbon-assimilation of plants is of great theoretical interest as an example of the simplest type of assimilation. The plant absorbs the carbonic acid, CO_2, and the rate of its intake therefore measures the rate of assimilation. The measurement of assimilation from the intake of CO_2 necessitates a complicated chemical analysis, which is therefore a very prolonged and laborious process. It is neither a very sensitive nor a highly accurate method. The following automatic method was therefore devised for recording normal rate of photosynthesis and for quickly indicating any change induced in that rate.

Automatic Recorder of Assimilation

Water-plants obtain their carbon from the carbonic acid dissolved in the water. When sunlight falls on these plants, carbonic acid gas is broken up, the carbon becomes fixed in the form of carbohydrates, and oxygen is evolved which rises as a stream of bubbles from the plant. The rate of evolution of oxygen thus measures the rate of assimilation.

Numerous difficulties were encountered in making this method practical; they have been completely removed by the Automatic Recorder. A piece of water plant, *e.g.*, *Hydrilla verticillata*, is placed in a bottle completely filled with tank-water containing sufficient CO_2 in solution, the open end of which is closed by a special Bubbler apparatus, for measuring the oxygen evolved. The Bubbler consists of a U-tube, the further end of which is closed by a drop of mercury acting as a valve. The oxygen evolved by the plant, entering the U-tube, produces an increasing pressure, which eventually lifts the mercury valve and allows the escape of a bubble of the gas. The valve then immediately closes until it is lifted once more for escape of another equal volume of gas (fig. 103). The movement of the mercury completes an electric circuit, which either rings

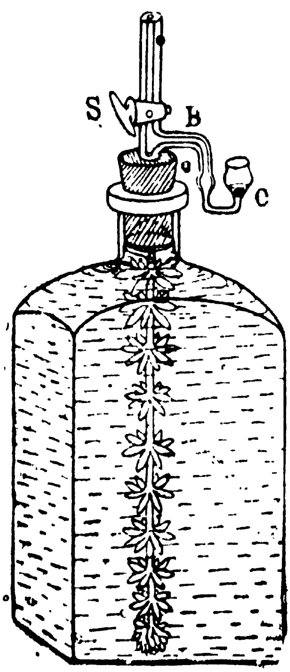


Fig. 103. The Plant-Vessel and the Bubbler.
S, stop-cock; B, Bubbler; O, mercury valve.

a bell or makes an electro-magnetic writer inscribe successive dots on a revolving drum (fig. 104). The

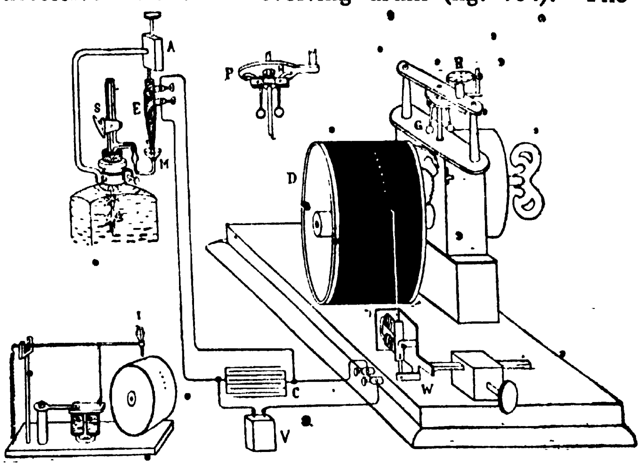


Fig. 104. The Automatic Recorder for Photosynthesis.

S, bubbler with stop-cock; E, the electric pencil for completing electric contact through drop of mercury, M; A, adjusting screw; V, voltaic cell; C, condenser; D, revolving drum; W, electro-magnetic writer; G, governor, shown separately at P with pair of hinged levers, H; I, ink-recorder. Electric bell not shown.

automatic method eliminates all personal errors of observation; it is so extremely sensitive that it is possible to indirectly measure by its means, a deposit of carbohydrate as minute as a millionth of a gram.

The following example illustrates the practical working of the apparatus. The plant with the apparatus is so placed as to face the northern light; the bell rings each time it has absorbed a certain amount of CO_2. If a person now stands obstructing the light, the assimilation is slowed down and the bell now strikes at longer intervals. When strong sunlight is thrown on the plant, the successive strokes on the bell become greatly quickened. The plant is such a sensitive detector of light that it may be employed as a photometer for indicating the slightest variations in the intensity of skylight.

The Hourly Variation of Assimilation

For this determination I took successive records from 7-30 a.m. until 5 p.m. for five minutes at a time. When the sun rose at 6-45 a.m. the light was too feeble to be effective. At 7-30 a.m. assimilation began, and the plant evolved four bubbles of oxygen in the course of five minutes; with the progress of the day it became

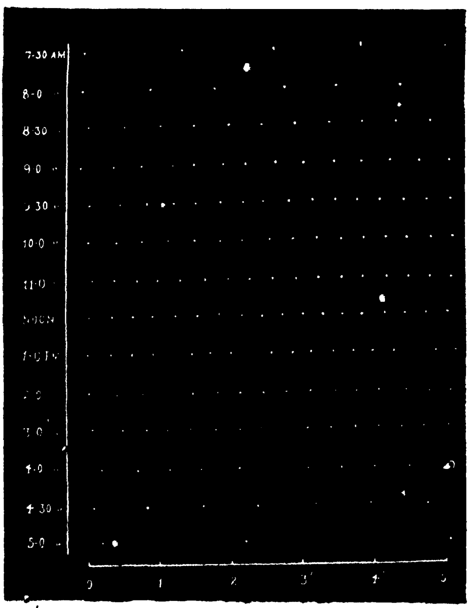


Fig. 105. Automatic Records of successive Bubblings for five minutes during different periods of the day.

Note the slow rate at 7-30 a.m. and 4-30 p.m., and the quick rate at mid-day.

more and more active until at 1 p.m., the activity increased four times that in the morning. The real reason for increased assimilation at 1 p.m. is the favourable condition of light and temperature. The activity declined in the afternoon and became arrested with the onset of darkness (fig. 105).

Effect of Infinitesimal Trace of Chemical Substance

One of the most unexpected results, was the discovery of the extraordinary increase in the power of assimilation by inconceivably small traces of certain chemical substances. It was found that when these were diluted, one part in a billion, they produced an increase in the power of assimilation of more than a hundred per cent. The immediate and concrete demonstration of minute traces of chemicals on assimilation is of special interest, since it enables us to understand the effects of infinitesimal quantities of vitamin on general assimilation and of hormones on physiological reaction.

Formaldehyde, which in large doses acts as a poison, is found in a solution of one part in a billion, to produce an increase of activity of 80 per cent. The stimulating effect of traces of formaldehyde has a special significance in regard to the 'first product' of photosynthesis. There is reason to believe that this first product is formaldehyde, which by polymerisation, becomes converted into carbohydrate. The poisonous nature of formaldehyde stood in the way of acceptance of this view, but the experiment just described shows that traces of this substance, instead of being poisonous, actually enhance the photosynthetic activity.

Efficiency of the Photosynthetic Organ in Storage of Solar Energy.

The results hitherto obtained indicate, in general, a very low order of efficiency in storage of energy. The methods employed have been defective from absence of means of exact measurement of the incident energy, from the indeterminate loss of the energy received and from the difficulty in the exact determination of the energy stored. The efficiency is found from the ratio of the energy stored Es, to the energy absorbed Ea.

$$\text{Efficiency} = \frac{Es}{Ea}$$

I have been successful in obviating the various difficulties in the accurate determination of the energy absorbed, and of the energy stored. The energy absorbed is found by two different methods, the Calorimetric and the Radiometric, these two independent determinations following each other in quick succession. While the energy absorbed is being determined, simultaneous measurement is made of the energy stored by the production of carbohydrate. This is calculated from the volume of oxygen evolved.

The efficiency of the photosynthetic organ is found to be much higher than had been usually supposed, being half that of an ordinary steam engine. In vigorous *Hydrilla* plant it is as high as 7·4 per cent.

The automatic method of record that has been described, can also be utilised in physico-chemical investigations, such as the determination of the rate of evolution of a gas under controlled conditions of temperature, of concentration, of intensity of light, of catalytic agents and others, either separately or in combination. It is obvious how it can be applied in various ways for measuring chemical reactivity or velocity of chemical reactions, *e.g.*, as in the study of Vant Hoff's Law, of the effect of light on chemical change and of other allied phenomena.

(*Physiology of Photosynthesis*, 1925.)

XXV

THE SELF-RECORDING RADIOGRAPH

A diurnal periodicity is generally exhibited in the various activities of the plant and in the movements of its different organs. This periodicity must be related to external variations, notably of temperature and light. It would be impossible to analyse the resulting phenomenon unless a continuous record of changes in the intensity of light is secured with the same exactitude as that of variation of temperature. As regards these two principal factors, the effect induced by the rise of temperature is often antagonistic to that of increasing intensity of light. A rise of temperature, for example, enhances the rate of growth up to an optimum ; light, on the other hand, acts as a stimulus in retardation of growth.

For full analysis of diurnal periodicity in plants, it thus becomes necessary to devise means for continuous record of variation of temperature and the changing intensity of light. In regard to the variation of temperature, a simple and reliable type of thermograph has been devised, by which it is easy to obtain a continuous record of the variation of temperature throughout the day and night. No apparatus is, however, available for the continuous registration of variation of the intensity of light.

The Selenium Cell

Selenium is well known for the characteristic diminution of its electric resistance under illumination.

When an electric current is maintained in the circuit, exposure of the selenium cell to light causes an increase of the galvanometer deflection. Several difficulties are, however, encountered in employing it for a continuous record of fluctuation of light for the whole day. The resistance of selenium undergoes a change under the polarising action of an electric current, the variation increasing with the strength and the duration of the current. The effect of polarisation is however negligible, if the current be feeble and of short duration. There is a possibility of another difficulty arising from the effect of daily variation of temperature on the normal resistance of the selenium cell. Allowance for this could be made by taking a continuous record of the effect of hourly variation of temperature on the resistance of the cell kept in darkness. Finally means have to be devised for automatic record of galvanometer deflections under changing intensities of light.

The Radiograph

The difficulties encountered in obtaining automatic record have been removed by the following devices :—

(*a*) The Wheatstone Bridge for balancing electric resistance of the selenium cell in dark and its upset on exposure to light.

(*b*) The arrangement of three electric keys which are automatically put on and off in regular sequence and at pre-determined intervals.

(*c*) The Self-recording Galvanograph.

The Wheatstone Bridge

This is diagrammatically represented in B (fig. 106). The resistance of the particular selenium cell S is 76,000 ohms in the dark. An approximately equal resistance is placed in the second arm of the bridge. A rheostat having a large number of turns of fine wire with a sliding contact is used for the two variable arms of the bridge, diagrammatically represented by a straight line. Under exact balance the galvanometer deflection is reduced to zero. The balance is upset when the selenium cell is exposed to light and the resulting deflection gives a measure of the intensity of light.

The Automatic Keys

After previous adjustment of the balance in the dark the electric circuit is completed by the closure of key K_1;

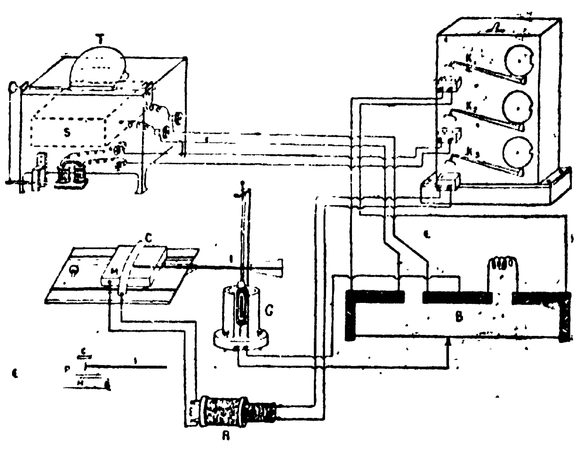


Fig. 106. The Self-recording Radiograph.

The selenium cell, S is periodically exposed to light by the electromagnetic shutter, T. The selenium cell forms one arm of the Wheatstone Bridge, B. The three keys, K_1, K_2, K_3, are periodically closed and opened by clockwork. G, the recording galvanometer with index, I, carrying double-pointed platinum at its end, which moves between the metal strip, C, and the plate, M. R, sparking coil with its electrodes connected with C and M. The battery is not shown in the figure (see text).

the selenium cell is next exposed to light by an automatic electro-magnetic shutter T. The deflection of the galvanometer is recorded by means of electric sparks on a piece of moving paper. The different operations are carried out in proper sequence by the automatic devices described below.

K_1 completes the battery circuit for about 10 seconds, by which time the record is completed. The successive records for variation of light are taken at intervals of 15 minutes; the periodic closures of the circuit are thus for 10 seconds at intervals of 15 minutes. This short passage of the current is found in practice to cause no polarisation.

The second key K_2 actuates an electromagnetic device by which the trap-door, T, is opened for the definite period of one second; the selenium cell S inside the dark box is thus exposed to light for this length of time. The trap-door is seen in the diagram immediately above the dark box. In reality it is at the upper end of a vertical tube the inside of which is coated with lamp-black to prevent side reflection. The light that falls on the selenium cell is thus from a definite area of the sky. The intensity of light from the sky at different periods of the day causes deflection of the galvanometer which is proportional to that intensity. The maximum deflection of the galvanometer employed is attained in the course of 3 seconds after the exposure.

The third key K_3 is for completion of spark circuit R for record of the maximum galvanometric deflection, three seconds after the exposure of the selenium cell. This key actuates a sparking coil R, the vibrating interrupter of which is not shown in the figure. The spark, thus produced, punctures the maximum deflected position of the galvanometer index on a moving piece of paper attached to the plate M.

The successive closure and opening of the keys are made automatically and in proper sequence by means of a clock work, the whole process being repeated at intervals of 15 minutes.

The Galvanograph

The most difficult problem is the automatic record of galvanometric deflections. This can be secured without any difficulty by means of photography. A spot of light reflected from the galvanometer mirror is in this case allowed to fall on a photographic plate which descends at an uniform rate by clockwork. This, however, entails the use of a dark room and subsequent development of the plate. The trouble was avoided by the device of direct record of the galvanometer deflection by means of electric sparks.

The sparking method has been previously employed in which the deflected index of the galvanometer in connection with one electrode of an induction coil leaves a spark record on a moving piece of paper. Several difficulties are, however, encountered in employing this method for record with a highly sensitive galvanometer. There is a liability of leakage of the high tension current into the galvanometer circuit. The discharge of the spark gives moreover a backward kick to the index by which the normal deflection undergoes an unknown variation.

The above difficulties have been removed in the following manner. The moving coil of the sensitive D'Arsonval galvanometer, has a long glass index I, at right angles to the plane of the coil. The glass index is coated with shellac varnish to render it highly insulating. The index is projected to a short distance on the opposite side, for attachment of a counterpoise; this takes the form of a vertical vane of mica which acts as a damper. The galvanometer itself is of an aperiodic type, and the addition of the damper makes it perfectly dead-beat. The sensitiveness of the galvanometer is such that a micro-ampere of current produces a deflection of 10 mm. of the index. The recording index has attached to it a short vertical piece of thin platinum wire pointed at its two ends; this end of the index moves between a sheet of metal M, on which is spread the recording paper, and a semi-circular piece of narrow metal sheet C. The metal sheet M is mounted on wheels and moves at an uniform rate by clockwork. Record is made by sparks. One electrode of the sparking coil is in connection with C, and the other with M. The sparking thus takes place simultaneously, above and below the vertical and double-pointed platinum wire carried at the end of the index. There is thus no resultant kick, and the index remains undisturbed. The sparking, as previously stated, takes place three seconds after exposure of the selenium cell to light, by which time the deflection reaches its maximum. The record thus consists of successive dots at intervals of 15 minutes, the dots representing the maximum deflections of the galvanometer corresponding to the intensities of light.

The record given in figure 107 was taken about the end of January; the sun rose at about 6-45 a.m. and set at 5-30 p.m. The twilight is very short in the tropics; the sky is feebly lighted about 6 a.m.; it becomes dark about 6 p.m. The record shows the intensity of light to be exceedingly feeble at 6 a.m. The rise in the intensity was rapid, attaining the maximum at 12 noon.

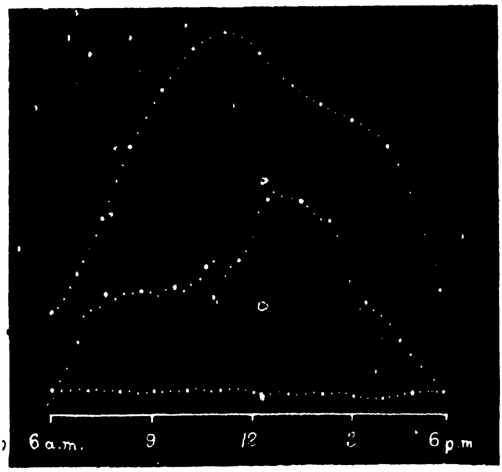


Fig. 107. Radiograph of variation of intensity of light from the sky during 12 hours in winter. The upper record shows the variation on a bright day, the maximum intensity being attained at 12 noon. The lower record exhibits irregular variation on a cloudy day. The practically horizontal record above the base line shows that the electric resistance of selenium cell is practically unaffected by variation of temperature. Successive thin dots at 15 minutes' interval, thick dots at intervals of an hour.

This will be designated as the light-noon. The intensity of light then declined at a rate slower than the rise; after 5 p.m. the fall of intensity was extremely rapid.

It was stated that there was a possibility of change of resistance induced by diurnal variation of temperature. In order to determine the extent of this variation, a spark record was also obtained before exposure to light. The dotted record near the base (fig. 107) shows that the resistance remained practically constant, inspite of the variation of the temperature.

An important point arises as regards the diurnal variation of light and of temperature, and determination of their periods of maximum and minimum. For this purpose records of diurnal variations of temperature and of light were taken on the same day in summer with the

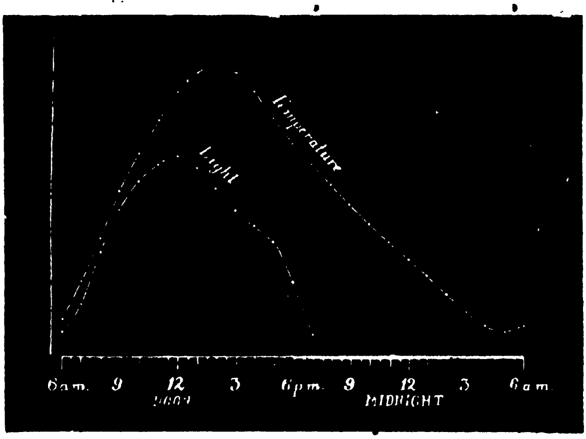


Fig. 108. Record of diurnal variations of light and of temperature in summer.

thermograph and the radiograph. The two curves are given in figure 108; it will be seen that while the maximum intensity of light is at 12 noon, the thermal maximum is at about 2 p.m. The thermal noon is thus two hours later than the light-noon. Light disappears at night from 6 p.m. to 6 a.m., that is to say, the period of minimum or zero light is prolonged for 12 hours. But the fall of temperature is gradual, and the minimum is attained at about 5 a.m. which is the thermal dawn. The characteristic variations of these two important factors should be borne in mind, since the diurnal movements of plants are modified by the algebraical summation of the effects of light and of temperature.

It is sometimes desirable to carry out researches during a period when the intensity of light remains approximately constant. This period is found to be between 11 a.m. and 1 p.m. for the variation is then only ± 5 per cent. of the mean.

The record given of the diurnal variation of light is true of days when the sky is clear. But the passage of clouds causes change in the intensity which is accurately recorded by the Radiograph. A record of such irregular variation in a stormy day is given in the lower record of figure 107.

(*Life Movements in Plants, Vol. IV,* 1923.)

XXVI

THE HIGH MAGNIFICATION CRESCOGRAPH

The difficulty of investigations on growth arises from its extreme slowness, which is two thousand times slower than the movement of the snail. The 'auxanometers' usually employed magnifies growth to about 20 times; under this magnification several hours must elapse before growth becomes perceptible. During this long period the external conditions, such as light and warmth, undergo change thereby confusing and vitiating the result. The external conditions can be kept constant for a few minutes only; hence the effect of variation of an individual factor can only be found by increasing the magnification to about ten thousand times and thus reducing the period of the experiment. The apparatus devised for this purpose not only produces this enormous magnification but also automatically records the rate of growth and its induced variation in the course of time as short as a minute or so.

The recorder consists of a compound system of two levers; the first magnifies a hundred times, and the second enlarges the first a hundred-fold, the total magnification being thus ten thousand times. The difficulty introduced by the weight of levers was surmounted by the employment of navaldum, an alloy of aluminium, which combines great rigidity with exceptional lightness. The friction at the points of support was removed by the employment of jewel bearings. The record is taken on a smoked glass plate kept oscillating to and from by means of a crank K and eccentric R, actuated by a clockwork C (fig. 109). Successive dots are produced at definite intervals which could be made to vary from 1 to 10 seconds.

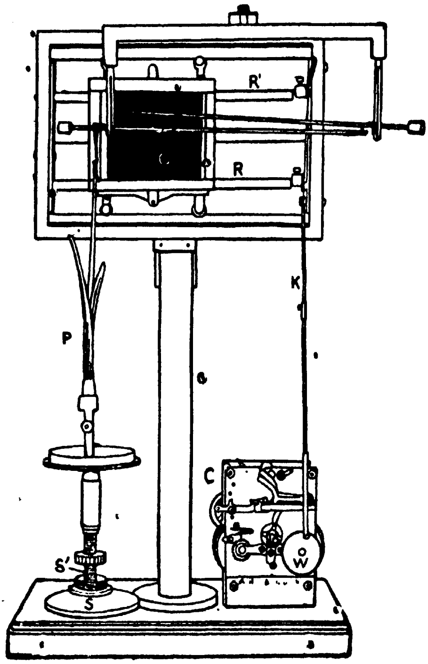


Fig. 109. The High Magnification Crescograph.

P, plant; C, clockwork for periodic oscillation of recording smoked glass plate G; S S', micrometer screws; K, crank; R, eccentric; W, rotating wheel.

Two different methods are employed for obtaining the record. In the first, the records are taken on a stationary plate, the first series under normal condition, and the second under a given variation. The increase or diminution of intervals between successive dots in the two series, demonstrates the stimulating or depressing nature of the changed condition, In the second method, the record is taken on a plate moved at a uniform rate by clockwork. A curve is thus obtained, the ordinate representing growth-elongation and the abscissa, the time. The increment of length divided by the increment of time gives the rate of growth at any part of the curve. As long as growth is uniform, so long the slope of the curve remains constant. Enhancement of the rate of growth by a stimulating agent causes an upward flexure of the curve ; a depressing agent, on the other hand, lessens the slope of the curve.

Determination of the Absolute Rate of Growth

The record of growth was taken with a vigorous specimen of *S. Kysoor* on a stationary plate.

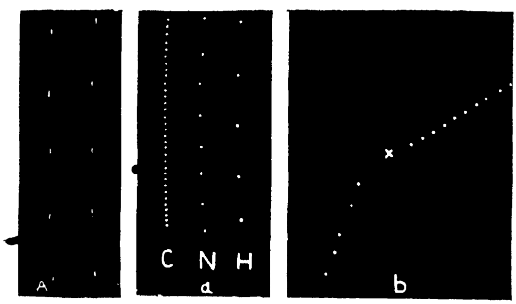


Fig. 110. Crescographic Records.

(A) Successive records of growth at intervals of one second (magnification 10,000 times). (*a*) Effect of temperature taken on a stationary plate ; N, normal rate of growth ; C, retarded rate under cold ; H, enhanced rate under warmth ; (*b*) record on moving plate, where diminished slope of curve denotes retarded rate under cold. (Magnification 2,000 times.)

For securing uniformity of growth, it is advisable that the plant be kept in darkness or uniform diffused light.

So sensitive is the recorder that it shows a change of growth-rate due to slight increase of illumination by the opening of an additional window. The oscillation frequency of the recording plate was once in a second, the magnification being 10,000 times. After taking the first series of record, the second series was obtained after an interval of 15 minutes (fig. 110A) The magnified growth elongation is 9·5 mm. per second; since it is quite easy to measure 0·5 mm., it is possible to record growth for a period as short as 1/20th of a second. It is further seen that the Crescograph enables us to magnify and record a length of 0·0005 mm. which is a fraction of a single wave length of light.

Employing one second, as the unit of time and μ or micron as the unit of length (1/1000 mm.), the absolute rate of growth of *S. Kysoor* is found as follows :—

If m be the magnifying power, l the average distance between successive dots in mm. at intervals of t seconds,

$$\text{the rate of growth} = \frac{l}{mt} \times 10^3 \text{ per second}$$
$$= \frac{9 \cdot 5}{10{,}000} \times 10^3 \text{ per second.}$$
$$= 0 \cdot 95 \ \mu \text{ per second.}$$

Effect of Variation of Temperature.

The effect of variation of temperature on growth is shown in fig. 110*a*. The middle series N was taken at the temperature of the room; the next C was obtained when the temperature was lowered by a few degrees. Finally H was taken when the plant chamber was warmed. The spaces between successive dots are shortened under cooling which induces a diminished rate of growth. The enhancement of the rate of growth by rise of temperature is exhibited by the widening of intervals between successive dots. The effect of lowering of temperature in retardation of growth is also exhibited by record (fig. 110*b*) taken on a moving plate, in which the diminished slope of the curve demonstrates the depressed rate of growth.

Effect of Chemical Agents

The effects of manures, anæsthetics, drugs and poisons, can be similarly determined in the course of a few minutes, and with unprecedented accuracy. A few agents only have hitherto been employed in stimulating growth, whereas there are numerous others of whose actions we have been profoundly ignorant. The crude method hitherto employed in the application of a few chemical agents and of electricity has not been uniformly successful. The cause of the anomaly is found in the discovery of an important factor, namely, the dose of application, which has hitherto not been taken into account. It was thus found that while a particular intensity of electrical current accelerated growth, any excess above a critical point retarded it. The same is true of chemical stimulants; a striking result was obtained with certain poisons which in normal doses killed the plant, but in doses sufficiently minute acted as a highly efficient stimulant in promotion of growth.

The Balanced Crescograph

The growth of plants is affected by changes of environment which are even below human perception. It now became necessary to devise a new method of still greater sensitiveness which would instantly show by the up- or down-movement of an indicator, the stimulating or depressing nature of an agent on growth. The desideratum is to compensate the up-movement of growth by some regulating device, by which the plant is made to descend exactly at the same rate at which the growing tip of the plant was rising, whatever that rate may be. The special difficulty encountered was in obtaining exact balance for widely varying rates of growth in different plants, and even in the same plant under different conditions. In the Balanced Crescograph, (fig. 111) a train of revolving clockwork actuated

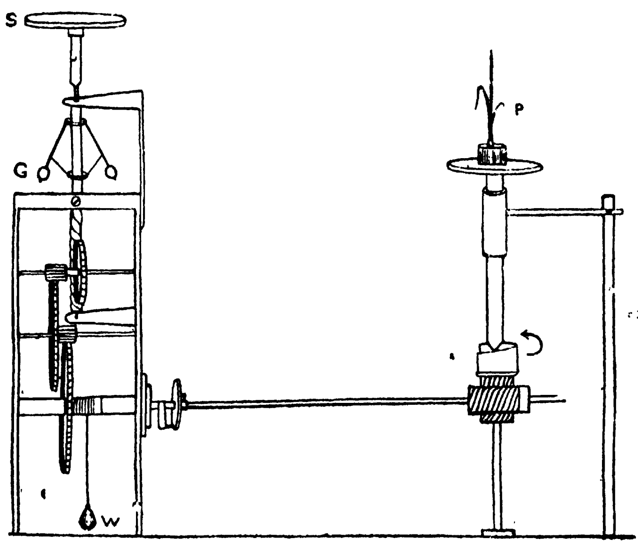


Fig. 111. The Balanced Crescograph.

Compensation of growth-movement produced by equal subsidence of the holder containing the plant (P). Adjusting screw (S) regulates the speed of the governor (G). W, heavy weight actuating clockwork.

by the fall of a weight, lowers the plant at the same rate at which it is growing. The exact adjustment is obtained by the gradual turning of a screw to the right or to the left, by which the rate of compensating fall is retarded or accelerated. In this way the rate of growth becomes exactly compensated, and the recorder now dots a horizontal line instead of the former curve of ascent. The turning of the adjusting screw of the Balanced Crescograph also moves an index against a circular scale (not shown in the figure) so graduated that its reading at once gives the rate at which the plant is growing at that instant. When balanced, the recording apparatus is extraordinarily sensitive. Any change, however slight, in the environment is at once indicated by the upset of the balance with up- or down-movement of the curve. This method is so extremely sensitive that it is possible to detect variation of rate of growth so excessively minute as 1/1500 millionth of an inch per second.

As an illustration of the delicacy of this method, a

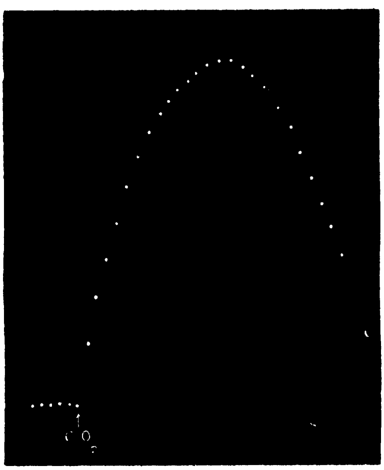


Fig. 112. Record showing the effect of carbonic acid gas on growth. Horizontal line at the beginning indicates balanced growth. Application of carbonic acid gas induces enhancement of growth, shown here by up-curve, followed by depression, exhibited by down-curve. Successive dots at intervals of ten seconds.

record is given of the effect of carbonic acid gas on growth (fig. 112). A jar is filled with this gas, and emptied over the plant; the invisible gas, on account of its heavier weight, falls in a stream and surrounds the plant. The record shows that this gave rise to an immediate acceleration of growth, which continued for two and-a-half minutes; this preliminary acceleration was followed by retardation of growth as shown by the down curve. The Balanced Crescograph thus not only exhibits the beneficial effect of an agent, but also indicates the dose which prolongs the beneficial effect.

Effect of Wireless Stimulation on Growth

Growth is modified by the action of visible light; two different effects are produced depending on the intensity. Strong stimulus of light induces a diminution while feeble stimulus induces an acceleration of the rate of growth. The effectiveness of light in modifying growth depends moreover on the quality of light; the effect is very strong in the ultra-violet region of the spectrum with its extremely short wave-length of light; it declines almost to zero as we move towards the less refrangible rays, the yellow and the red, with their comparatively long wave-length. As we proceed further to the infra-red region we come across the vast range of electric radiation, the wave-lengths of which vary from the shortest wave I have been able to produce (0·6 cm.) to others which may be miles in length. There thus arises the important question whether plants perceive and respond to the long ether-waves, including those employed in signalling through space.

At first sight this would appear to be very unlikely, for the most effective rays are in the ultra-violet region with wave-length as short as 20×10^{-6} cm.; but electric waves used in wireless signalling are 50,000,000 times as long. The perceptive power of our retina is confined within the very narrow range of a single octave, the wave-lengths of which lie between 70×10^{-6} cm. and 35×10^{-6} cm. It is difficult to imagine that plants could perceive radiations so widely separated from each other as the visible light and the invisible electric waves.

The results obtained prove, however, that electric waves are effective in modifying the rate of growth. The experiment was carried out with the help of a portable electric Radiator, the intensity of radiation being capable of variation. The Radiator was placed at a distance of 200 metres from the growing plant which was suitably mounted on the Balanced Crescograph.

Effect of feeble Stimulation.—The response was found to be an acceleration of growth as seen in fig. 113 (*a*). This is analogous to the stimulating action of light of sub-minimal intensity.

Effect of strong Stimulation.—Even more striking is the effect of stronger stimulation; the balance was immediately upset, indicating a retardation of the rate of growth (fig. 113 *b*). The latent period, *i.e.*, the interval between the incident wave and the response, was only a few seconds. The record given in the figure was obtained with the moderate magnification of 2,000 times.

Under an intensity of stimulus slightly above the sub-minimal, the response exhibited retardation of growth followed by quick recovery, as seen in the series of records given in figure 113 (c). The perceptive

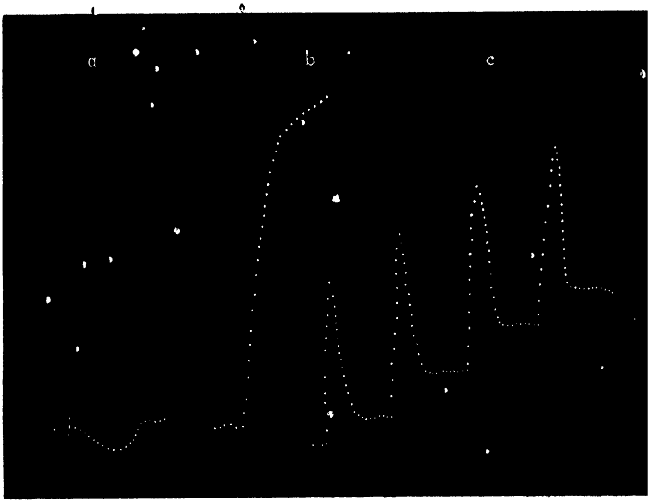


Fig. 113. Record of responses of plant to wireless stimulation. (*a*) Response to feeble stimulus by acceleration of growth ; (*b*) response to strong stimulus by retardation of growth ; (c) response to medium stimulation—retardation followed by recovery. Down-curve represents acceleration, and up-curve retardation of growth (seedling of wheat).

range of the plant is inconceivably greater than ours ; it not only perceives, but also responds to different rays of the vast ethereal spectrum.

(*Proc. Roy. Soc. Oct.* 1917 *and Transactions Bose Institute,* 1919.)

XXVII

THE MAGNETIC CRESCOGRAPH AND THE MAGNETIC RADIOMETER

In winter the growth appears to be in a state of arrest; in reality growth may persist but its rate is too slow to be detected even by the High Magnification Crescograph in which two levers produce a compound magnification of 10,000 times. It may be thought that further magnification could be obtained by a compound system of three levers; there is, however, a limit to the number of levers that may be employed with any advantage, for the slight overweight of the last lever becomes multiplied, exerting a tension so great on the plant as to interfere with the normal rate of its growth. The friction at the bearings also becomes added up by an increase in the number of levers which obstruct the free movement of the last recording lever. Magnification requiring additional material contact between different levers have, therefore, to be abandoned and it became necessary to devise an ideal method of magnification without contact. In the device perfected for this purpose a single magnifying lever attached to a growing plant upsets a very delicately balanced magnetic system (cf. fig. 114). The indicator is the reflected spot of light from a mirror carried by the deflected magnet. I have thus been able to produce a magnification as high as 50 million times. This order of magnification would lengthen a single wave of sodium light to 2,500 cm. It is obvious that this method of super-magnification would be of great help in many physical investigations.

The Demonstration Crescograph

Such an enormous magnification can not be employed in ordinary investigations on growth, for the indicating spot of light rushes on like a flash. I had, therefore, to reduce the magnification to a million times by which demonstrations of a striking character on various phenomena of growth can be given before a large audience. The following may be taken as a typical example :—

The normal rate of growth of the experimental flower-bud of *Crinum Lily* was 0·0006 mm. per second. A scale 3 metres long divided into centimetres was placed against the screen. A metronome beating half seconds is started at the moment when the spot of light transits across the zero division ; the number of beats is counted till the index traverses 300 cm. At the normal temperature of the room (30° C.) the index traversed 300 cm. in 5 seconds. As it is easy to measure 1 mm. on the scale, the Magnetic Crescograph enables measurement of growth in a period shorter than 1/500th of a second.

After observing the normal rate at the temperature of the room, the plant chamber was cooled to 26° C. by blowing in cooled water vapour ; the time now taken by the spot of light to traverse the scale was 20 seconds, *i.e.*, the growth-rate was depressed to one-fourth. Under continuous lowering of temperature there was a continuous retardation, till at 21° C. growth was arrested. Warm vapour was next introduced raising the temperature of the plant-chamber to 35° C. The spot of light now rushed across the whole length of the scale in $1\frac{1}{2}$ seconds, growth being enhanced to more than three times the normal rate. The entire series of experiments on the effect of variation of temperature on growth was completed in the course of 15 minutes.

Experimental demonstrations of the action of light, and of various chemical agents can also be given in a similar manner.

The Magnetic Radiometer

As an example of the application of the method of high magnification in physical investigations, I describe the Magnetic Radiometer in determination of the energy of different rays of the solar spectrum by measuring the elongation of a metallic wire coated with lamp-black. The particular spectral ray falling on the wire is absorbed, and thus raises the temperature proportionately to the energy of radiation. The resulting increase of length is so minute as to be undetectable by any method of magnification hitherto available.

A diagrammatic representation of the apparatus is given in fig. 114. W is a length of zinc wire which becomes lengthened by rise of temperature produced by absorbed radiation. It is attached by a hook to the short arm of a long magnetic lever, the N end of which is lowered by any elongation of the sensitive wire. In front of the N end of the magnetic lever is suspended a small magnetic needle with an attached mirror. As the N pole of the magnetic lever is lowered, it produces an increasing deflection of the suspended needle, which is magnified by the spot of light reflected from the attached mirror. The sensitiveness of the apparatus is very greatly enhanced by the employment of a perfect system of astatic needles.

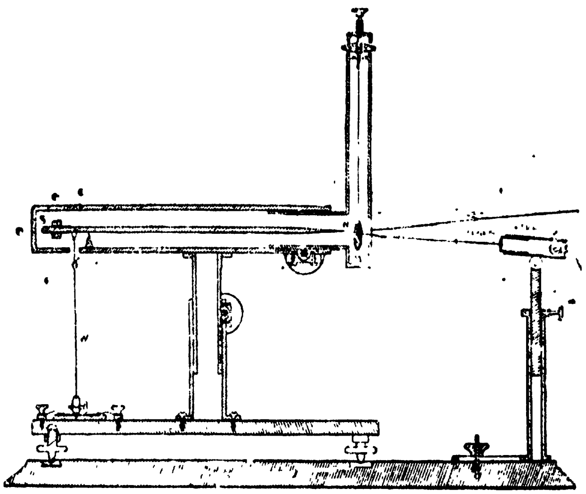


Fig. 114. The Magnetic Radiometer.

SN, magnetic rod supported on fulcrum; short arm of magnet attached to sensitive strip of metal W. Elongation of strip lowers the N end, which causes deflection of the suspended needle with attached mirror M. Deflection magnified by reflected spot of light.

This method for the measurement of radiation is extraordinarily sensitive. For instance, there is an apparatus permanently adjusted in the Institute in which the sensitive element is a thin strip of ebonite which is enclosed in a tube with a narrow slit in front. When any person walks at some distance past the instrument, the indicating spot of light remains perfectly quiescent until the individual is in line of sight of the sensitive strip; a sudden deflection is then produced by the radiation which is emitted from the human body, through thick warm clothing and a heavy overcoat; when the person walks past the line of sight the indicating spot of light returns to its original zero.

The zinc wire was surrounded by a wooden tube with a narrow slit for the passage of the spectral rays. The slit was open through a length of 10 cm., the brass piece to which the strip was soldered being protected from radiation. A very thin piece of mica covered the slit, to prevent air-currents getting access to the narrow chamber in which the sensitive strip was enclosed. The exceedingly thin piece of mica was found practically to have no effect in obstructing radiation. The whole apparatus was placed inside a larger wooden box covered with non-conducting felt. A round hole in front of the box (covered with a piece of thin glass) allowed the passage of the spot of light reflected from the mirror attached to the suspended magnetic needle.

It is necessary to give a detailed account of precautions to be observed, because the instrument is so sensitive that it detects the slightest difference in the temperature of the different portions of the same mass of air. Gases are highly non-conducting, and their temperature hardly attains a perfect uniformity. In these circumstances it is best to take precautions against contact of the strip with the outside air, which, again, should not be disturbed in any way. The observer never moves from his place in the dark room, which is closed on all sides.

The spectrum produced by the carbon disulphide prism was found to extend beyond the limit of the visible red, this extension into the infra-red region being almost 6 cm., or about one-third the breadth of the visible spectrum.

The extreme sensitiveness of the Radiometer was also exhibited by its discrimination of the radiation components of the morning and midday light. In the morning the intensity of the blue rays in the spectrum was found to be slightly less than at midday. This is due to the greater scattering of the short waves by the thicker stratum of the atmosphere through which the light has to pass in the morning.

The energy of radiation in the different regions of the spectrum was compared on January 16 and 19, 1923. It should be remembered that the determination of the energy of the different rays was made upon the spectrum given by the carbon disulphide prism. The following results for the 16th and 19th January are seen to be practically the same.

Table showing the Distribution of Energy in the Spectrum produced by the CS_2 Prism

Wave-length.	Energy of radiation. 16th January.	Energy of radiation. 19th January.	Mean.
Infra-red { 850 μμ (?)	90	80	85
Infra-red { 790 μμ (?)	148	146	147
A 760 ,,	146	144	145
a 720 ,,	135	129	132
B 680 ,,	120	120	120
C 656 ,,	96	98	97
D 590 ,,	72	70	71
E 527 ,,	43	41	42
F 486 ,,	28	26	27
G 430 ,,	12	8	10

Radiation was detected at some considerable distance beyond the extreme red. At about 850 $\mu\mu$ the mean deflection of the Radiometer was found to be 85 divisions; at 790 $\mu\mu$ the energy was found to be 147, which was the maximum. At A (760 $\mu\mu$) the deflection declined to 145; at *a* (720 $\mu\mu$) it was reduced to 132; C (656 $\mu\mu$) gave a deflection of 97. At the sodium line D (590 $\mu\mu$) the reading was 71; the energy of the spectrum underwent a further and continuous decline; at E, F, and G the deflections were 42, 27, and 10 respectively.

(*Physiology of Photosynthesis*, 1925.)

XXVIII

THE RESONANT RECORDER

The exact determination of extremely short intervals of time is an important problem in various investigations. This is specially so in the measurement of time relations of different phases of response of living tissues.

When the sensitive pulvinus of *Mimosa pudica* is directly stimulated, say by an electric shock, a responsive contraction and fall of the leaf is initiated after the lapse of a short interval. After the completion of the fall of the leaf the contracted pulvinus slowly recovers as seen in the re-erection of the leaf. The lost time between the incidence of stimulus and the beginning of responsive movement is designated as the *Latent Period*. If instead of direct stimulation of the pulvinus, stimulus be applied on the petiole at a certain distance from the motile organ, then an excitatory impulse is transmitted through the intervening distance. The time-interval between stimulus and response will now be longer than under direct stimulation; the latent period of the pulvinus and the length of transmission afford sufficient data for the determination of the velocity of excitatory impulse in the plant, which I have shown elsewhere, is analogous to the nervous impulse in the animal.

The response of Mimosa is recorded by means of a writing lever suitably attached to the leaf (fig. 115).

The friction of the writing point against the smoked glass surface, however, introduces serious error in the accurate record of the amplitude and time-relations of the response-curve. The difficulty has been overcome by the writer being thrown into resonant vibration in

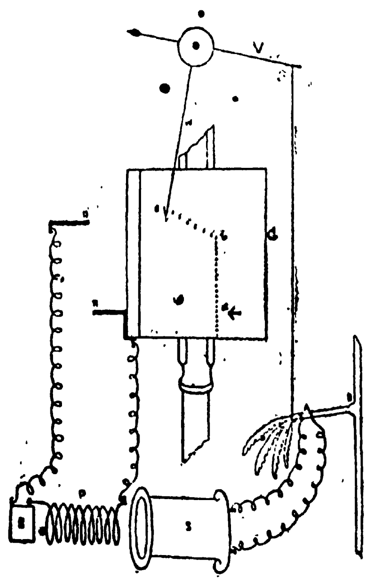


Fig. 115. Diagrammatic representation of the Recorder.

V, one arm of lever attached to leaf; W, the writer. The falling plate during descent makes electric contact of R with R′, causing induction-shock by the secondary coil S. Stimulus applied at *a* causes response later, at *b*.

consequence of which the record consists of a series of dots; the error arising from friction of continuous contact is thus completely avoided.

The Resonant apparatus consists of the writer, made of fine steel wire tuned in different cases, to vibrate

10, 20, or 200 vibrations per second. The writer is suspended at the centre of a circular electromagnet, the current in which is periodically interrupted by the reed C (fig. 116). When the writer and the reed are exactly tuned then the vibration of the reed throws the writer into a sympathetic vibration.

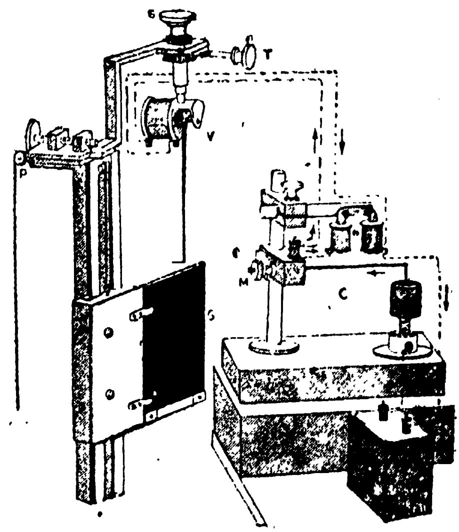


Fig. 116. Upper part of Resonant Recorder. (From a photograph.)
Thread from clock, not shown, passes over pulley P, letting down recording-plate; S, screw for vertical adjustment; T, tangent-screw for exact adjustment of plane of movement of recorder parallel to writing-surface; V, axis of writer supported perpendicularly at centre of circular end of magnet; C, the vibrating reed; G, smoked glass plate.

Determination of the Latent Period.

The reliability and accuracy of this method of automatic record of extremely short intervals of time is shown in the following curve (fig. 117) which gives the latent period of the pulvinus of Mimosa. The writer

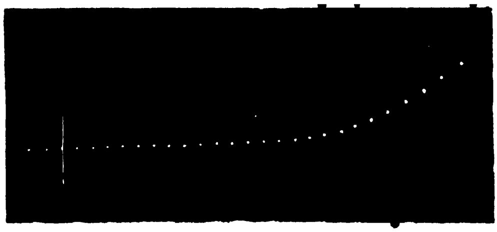


Fig. 117. Record of Latent Period of Mimosa with 200 Vibration Recorder.

was tuned to vibrate 200 times in a second, and the interval between successive dots therefore represents 1/200 of a second. It is not difficult to measure one-fifth of the distance between successive dots, and calculation can therefore be carried into thousandths of a second. In the present case there are 15·2 spaces between the stimulus and the initiation of response. The latent period of the specimen is therefore 0·076 of a second. The average value of the latent period of the pulvinus of Mimosa is found to be 0·1 second.

Determination of the Velocity of Impulse

The complete apparatus is shown in figure 118. An electrical shock was in the following experiment applied on the petiole at a distance of 30 mm. from the pulvinus, at the instant marked by the vertical line (fig. 119). The frequency of vibration of the writer was 10 per second. The interval between stimulation and the beginning of response is 16·2 spaces, or 1·62 seconds. A repetition of the experiment gave the same result. Stimulus was next applied directly on the pulvinus and the latent period was found to be about

0·12 seconds. The velocity of transmission of excitation in the particular specimen was thus found to be

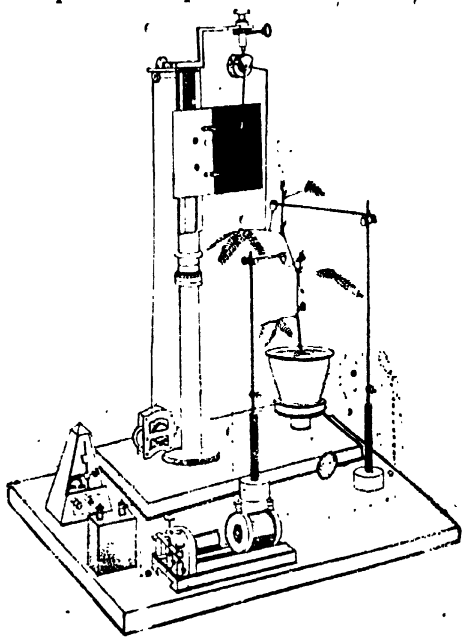


Fig. 118. Apparatus for determination of Latent Period and Velocity of Transmission of Excitation in *Mimosa.*

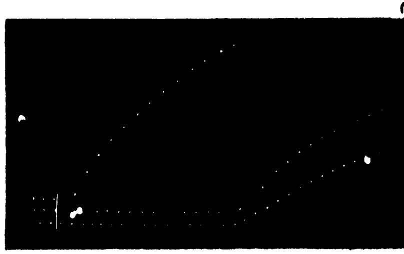


Fig. 119. Determination of velocity of Transmission of Excitation in petiole of Mimosa. Two lower records are in response to indirect stimulation applied at a distance of 30 mm.; upper record of response to direct stimulation gives the latent period. Recorder tuned to 10 V per second.

20 mm. per second. In thinner specimens the velocity is often found to be as high as 400 mm. per second. The velocity of impulse in Mimosa is slower than the nervous impulse in higher but quicker than that in lower animals.

The transmission of excitation is correspondingly modified by all conditions which modify the transmission of excitation in the animal nerve. The polar action of a constant electric current is identical in the two cases. In both Mimosa and animal nerve the velocity of transmission is increased within limits by a rise of temperature (fig. 120). In both, transmission

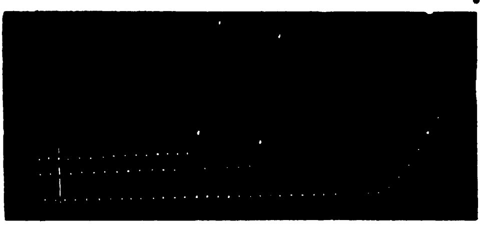


Fig. 120. Effect of Rise of Temperature in enhancing Velocity of Transmission. The three records from below upwards are for temperatures of 22° C., 28° C. and 31° C. respectively.

can be arrested temporarily or permanently by various physiological blocks. The conducting power is temporarily arrested by a block produced by the passage of an electric current in a portion of the conducting tissue through which the impulse is being transmitted; this electrotonic block is removed on the stoppage of the current. Finally, poisonous solutions abolish the conducting power of both animal and plant. These results offer conclusive proof that the conduction in the plant is a phenomenon of propagation of protoplasmic excitation as in the nerve of the animal.

The characteristics of contractility and conductivity are thus shown to be exhibited not only by animal but also by plant tissues. In the animal the cardiac tissue exhibits automatic and rhythmic pulsations. In the plant a similar activity is manifested by the leaflet of *Desmodium gyrans*, the well known Telegraph plant.

The Resonant Cardiograph

The record of the pulsation of the animal heart by the Cardiograph labours under the unavoidable difficulty of continuous frictional contact introducing error in the correct record of the amplitude and time-relations of the heart-beat. The drawback of continuous contact has been removed in my Resonant Cardiograph which records the pulsation with great precision by means of periodic dots, the Cardiogram being also its own chronogram. The automatic method of registration of extremely short intervals of time can be utilised with great advantage for this and other investigations.

The Characteristics of Cardiac Pulsation.

The Resonant Cardiograph inscribes the different phases of the heart-beat with unprecedented accuracy. The systolic contraction and its persistence, the diastolic expansion and the subsequent pause, and any variation of these under external agencies, can thus be quantitatively determined. The cardiograms of different animals show, moreover, certain characteristic differences in regard to time-relations, as illustrated by records of tortoise, of frog and of Ophiocephalus fish given below.

The writing lever was tuned to vibrate 20 times in a second, the magnification produced being about 8 times. The time-relations, it is to be remembered, is found from the intervals of successive dots $\frac{1}{20}$ second apart. The records show the auricular contraction preceding the ventricular. The period of a complete cycle is much longer in tortoise. The total period is 34 dot-intervals, or 1·7 seconds. In the particular specimen of frog the total period is represented by 14 dot-intervals or 0·7 second, while in the fish it is 16 dot-intervals or 0·8 second. Again in tortoise after the commence-

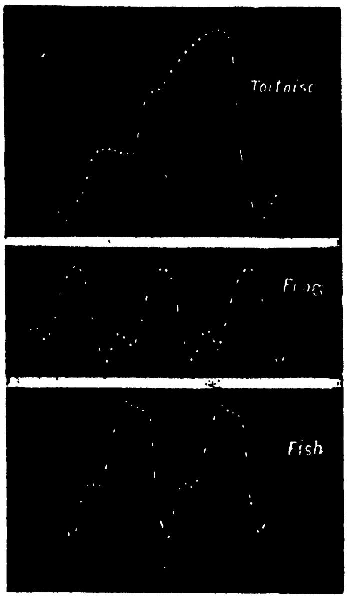


Fig. 121. Characteristic cardiograms of tortoise, frog and fish. The successive dot-intervals represent 0·05 sec.

ment of the less pronounced systolic contraction of the auricle, the contractile wave reached the ventricle in the course of 0·6 second, whereas in the frog and in the fish the interval is only 0·2 second, or one-third that in tortoise. The records show other characteristic differences and give very striking visual demonstration of the relative activity at different phases of the pulsation. When the activity is very great the markings are very wide apart and the dots are lengthened into dashes; with slowing down of activity the dots become thin and drawn close together (fig. 121). Under the action of depressing agents the post-diastolic pause becomes greatly prolonged.

Similarity of Rhythmic Mechanism in Animal and Plant

I have demonstrated elsewhere the remarkable similarity of rhythmic mechanism in animal and plant. In both, lowering of temperature slows down the pulsation culminating in an arrest. Rise of temperature up to an optimum, on the other hand, enhances the frequency. Diminution of internal pressure causes an arrest in both. The rhythmic tissue in animal and plant, has a long refractory period. In both, application of external stimulus has no effect during systolic phase of contraction, whereas an extra-pulsation is produced by stimulus during the diastolic phase of expansion.

The effect of drugs is often remarkably similar in the two cases. Dilute solution of potassium bromide causes a depression of cardiac pulsation; this depression is removed by the physiological antagonism produced by certain drugs.

I have recently been engaged in investigating the action of various medicinal plants of India on the activity of the animal heart. Among these I find that a heart in a state of depression is greatly stimulated by extracts of *Abroma augusta*.

In the following record the normal heart-beat of fish is seen to be greatly depressed by KBr solution. Subsequent application of Abroma extract caused a remarkable revival of activity (fig. 122). Even more remarkable

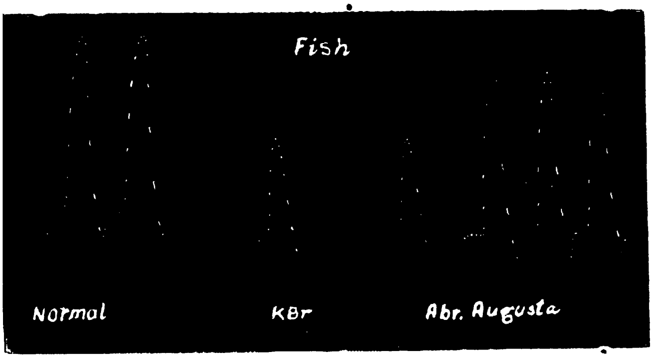


Fig. 122. Effects of depressant and stimulant on Cardiac pulsation of fish. The first series represents normal pulsation; the second, depression under KBr solution; the third exhibits revival by Abroma extract.

are the exactly parallel reactions of K Br and Abroma on rhythmic pulsations of Desmodium gyrans (Fig. 123).

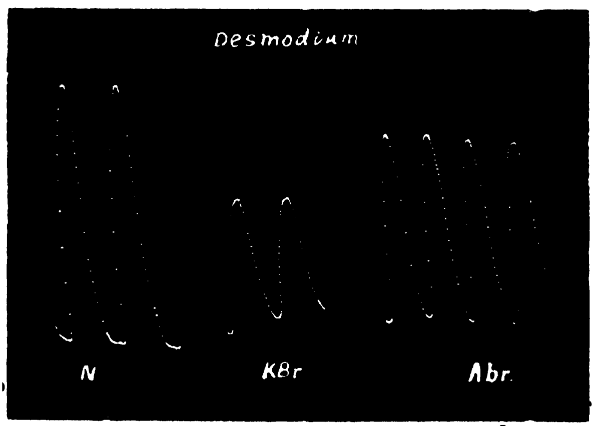


Fig. 123. Effects parallel to the above in pulsations of Desmodium plant.

XXIX

GENERAL SUMMARY

The investigations described in the present volume are on: A, the optical properties of electric waves; B, the characteristics of metallic-contact receivers which respond to electric radiation, either by a diminution or an increase of resistance; C, different types of molecular receivers which respond to diverse modes of stimulation; D, the similarity of response of inorganic and living substances; E, the physiological response of plants; and F, the identity of physiological mechanism in animal and plant.

A. Optical Properties of Electric Waves

Electric waves of great length curl round corners; accurate angular measurements are thus rendered impossible. The difficulty has been obviated by securing a narrow beam of electric radiation of relatively short length.

1. *Complete Electric Wave Apparatus*

The Radiator.—Electric radiation is produced by a single spark between two hemispheres and an interposed small sphere of platinum, the wave-length being reduced to about 5 mm. The sparking coil and battery are enclosed in a small double-walled metallic box with a tube for the passage of the electric beam. Magnetic disturbance due to the make and break of the sparking coil was found to affect the receiver; the magnetic disturbance was eliminated by making the inner box of soft iron which acted as a magnetic screen.

The Receiver.—A satisfactory form of receiver was constructed of steel or of nickel; a single point contact receiver made of steel, nickel, aluminium or magnesium is also found to be highly sensitive and reliable. The sensitiveness can be exalted to any degree desirable by adjustment of electromotive force acting on the circuit. Angular measurements are made with the spectrometer circle (p. 87).

2. *Selective absorption*

The transparency or opacity of various substances, brick, wood, pitch and others as well as strata of different liquids and solutions can easily be demonstrated by interposing them on the path of electric beam. Water is opaque on account of absorption of radiation; liquid air is, on the other hand, quite transparent. Sheets of metal do not transmit, but reflect the beam according to laws of reflection. A long trough filled with irregularly shaped pieces of pitch is opaque on account of multiplicity of reflection and refraction. It becomes more or less transparent when partial homogeneity is restored by pouring in kerosene (p. 89).

3. *Determination of Index of Refraction*

The prism method is quite unsuitable for exact determination of the index for the electric ray. Accurate results have, however, been obtained by the method of total reflection. The rotation of two semi-cylinders separated by parallel air-space, produce a sudden extinction of the image at the critical angle. The index of refraction of glass for the electric ray is found to be

2·04, which is much higher than the index 1·53 for the sodium light. The index for sulphur is 1·73 (pp. 21, 31).

4. *Influence of Thickness of Air-space on Total Reflection*

On account of extreme shortness of wave-length of the visible rays, the thinnest air-film produces total reflection at the critical angle. The case is, however, different with comparatively greater wave-length of electric radiation. The critical thickness of air-space is modified by the angle of incidence and by the wave-length. When a cube of glass is interposed between the radiator and receiver placed opposite to each other, the radiation striking one face perpendicularly is transmitted across the opposite without deviation and causes response of the receiver. On cutting the cube across a diagonal, two right-angled isosceles prisms are obtained. When the two prisms are separated slightly, keeping the two hypoteneuses parallel, thus securing parallel air-space, the incident radiation is found divided into two complementary portions, of which one is transmitted and the other reflected by the air-film at right angles to the incident ray. When the thickness of air-space is reduced to about 0·3 mm., there is a complete transmission and no reflection. The two prisms in spite of the breach due to the air-space, are electro-optically continuous. A greater separation of the two prisms increases the reflected, at the expense of the transmitted portion ; and at a certain critical thickness, there is no transmission but total reflection. If a thin piece of cardboard or any other refracting substance be next interposed, a portion of the radiation becomes transmitted, necessitating further separation of the prisms to reduce the transmitted portion to zero. This offers a means of determination of the index of refraction of plates of different substances (p. 44).

5. *Double-refraction and Polarisation*

The shortness of wave-length of electric radiation has enabled investigations on the polarising action of even small crystals. The polariser and analyser are made of fine wire gratings; they can also be made of a number of crystals such as Nemalite, Chrysotile, Serpentine and Epidote. The most perfect polariser and analyser are constructed of jute-fibres or of a book, both of which produce complete polarisation of the electric ray. Crystals of tetragonal, orthorhombic, hexagonal, monoclinic and triclinic systems produce double refraction and polarisation. Locks of human hair and vegetable fibres also produce polarisation (p. 96).

6. *Double refraction by strained dielectric*

Various stratified rocks exhibit very strong double refraction when the plane of stratification producing polarisation, is inclined at 45° to the crossed polariser and analyser, there being no effect when this plane is parallel to either the polariser or the analyser. Unannealed glass and ebonite also produce double refraction and polarisation of the electric ray (p. 95).

7. *Double absorption and double conductivity*

Certain crystals like Nemalite, Chrysotile and Epidote exhibit selective transparency to polarised radiation; these are transparent in one direction but opaque in a direction which is perpendicular to the first. Complete polarisation is due to their property of double absorption. Investigations showed that they also exhibit unequal electric conductivity in the two directions and that the direction of maximum conductivity is also the direction of maximum absorption. Electric vibrations perpendicular to the direction of maximum conductivity are thus alone transmitted, the emergent beam being thus completely polarised (p. 75).

8. *The Production of a "Dark Cross"*

The interposition of a circular structure like that of a disc of rolled paper on the path of polarised electric radiation is found to project a dark cross into space, the outline of which can be definitely found by means of the exploring detector. The production of a dark cross can also be demonstrated by woody stems with concentric rings as also by ringed concretion of flint round a central nodule. Stalactite also gives similar results (p. 115).

9. *Rotation of Plane of Polarisation*

Right handed and left handed rotations of the plane of polarisation are produced by oppositely twisted jute elements. The electro-optic analogues of two varieties of sugar, dextrose and levulose, were thus obtained. An apparently inactive variety was produced by a mixture of equal numbers of positive and negative elements (p. 109).

B. The Characteristics of Metallic-contact Receivers

The systematic study of effect of electric waves on contact-resistance of various metals and metalloids showed certain characteristic differences.

1. *Positive and negative classes of substance*

In regard to the variation of resistance induced by electric waves, it is found that substances could be divided into two classes positive and negative. The positive represented by Iron, Magnesium, and others, characteristically exhibits a diminution of resistance; the negative (Potassium, Arsenic, etc.) exhibits on the other hand, an increase of resistance. An intermediate class is found in Silver which under different molecular modifications, exhibits either a diminution or an increase of resistance. Some of these substances, moreover, exhibit an automatic recovery on the cessation of electric radiation (p. 125). The increase of resistance induced by electric radiation and automatic recovery prove that the theory of 'coherence' is inadequate in explanation of the phenomenon. The induced variation of resistance positive or negative, increases with the intensity of radiation. Under continued radiation a maximum effect is produced; there is now a balance between conductivity distortion and force of restoration, recovery becoming complete on the cessation of radiation. These and other facts prove that radiation induces a molecular change of an allotropic character, and that the variation of conductivity is an expression of the induced molecular change (p. 161).

2. *Molecular Recovery*

When the range of electric elasticity is not narrow, the substance exhibits an automatic recovery. In other substances the recovery is more or less prolonged. Even in such cases the recovery is hastened by molecular vibration produced by a mechanical tap, or by heat. These restore the sensitive substances from the state of induced molecular strain (attended by change of conductivity) to their original condition and original conductivity. In the positive class, a tap or application of heat restores the substance to original condition by an increase of resistance; in the negative class the restoration is by a diminution of resistance to the normal (p. 158).

3. *Characteristic Cyclic curves under E. M. Variation*

The conductivity change is produced not only under very rapid electromotive variation by electric waves, but also by a comparatively slow electric variation. Electric conduction in metallic particles sensitive to electric radiation does not obey Ohm's Law. The conductivity is not constant and independent of E. M. F. but varies with it. The two classes of substances, positive and negative can be discriminated from each other by their characteristic curves under cyclic electromotive variation.

The characteristic curve is obtained by recording the variation of the electric current produced under increasing E. M. F. For surface contact of positive class of substance like iron, the curve is concave to the axis of current. Under cyclic E. M. F. variation, the forward and return curves do not coincide; there is a hysteresis. The greater is the range of E. M. F. the greater is the area enclosed. The residual effect can be dissipated by mechanical vibration.

In the negative class of substance like potassium, the curve is of an opposite character being *convex* to the axis of the current. Increase of E. M. F. produces an actual diminution of current or an increase of resistance. This class exhibits an increase of resistance under electric radiation (p. 251).

C. Different Types of Molecular Receivers

External disturbances or stimuli impinging on a substance induce a molecular upset, the effectiveness of the stimulus depending on the rapidity of the onset of the disturbance. The molecular upset is attended by changes induced in the properties of the substance. The most sensitive means for its detection is electrical: by the method of conductivity or of electromotive variation (p. 170).

Stimulation of the substance can be produced by electric radiation, by visible light, and by mechanical vibration.

1. *Continuity of Effect of Electric Radiation and Light*

Method of conductivity variation.—This is specially well suited for studying the effect of electric radiation on discontinuous particles; for since the action of radiation is one of surface layer, the larger the area, the more pronounced is the effect, and in loose particles the effective surface is greatly enlarged. The effective total resistance of the particles, moreover, is due to the resistances of surface contacts; any change in the property of the surface layer therefore causes a great variation of the total resistance. There are two classes of substance of which the positive responds by a diminution and the negative by an increase of resistance (p. 135). The effect of radiation is annulled by mechanical vibration. The continuity of effect of electric radiation and light is seen in the galena receiver which responds to both visible and invisible lights by a diminution of resistance (p. 269).

Method of electromotive variation.—A difference of electromotive force is generated between two areas of the same substance, when one is exposed and the other shielded from electric or visible radiation. The characteristics of response to electric radiation and light under diverse conditions are found to be essentially similar (p. 187).

2. *Response to Mechanical Vibration*

Rapid mechanical vibration, also induces an electromotive variation between the stimulated and unstimulated portions of the same wire (p. 195). The response to mechanical stimulation is found to be of opposite sign to that under light as demonstrated by alternately subjecting one of the two wires of a strain cell to the two modes of stimulation. It is moreover possible to exactly balance the effect of one by that of the other, a slight increase or decrease of either producing an immediate upset of the balance in one direction or its opposite (p. 206).

3. *Molecular Response common to Electric Radiation, Light and Mechanical Vibration*

1. The molecular effect induced by stimulus can be detected in all cases by the methods of conductivity or of electromotive variation.

2. Substances exhibit quick recovery after moderate stimulation ; the recovery becomes protracted in consequence of overstrain caused by intense stimulation.

3. Response is modified by the previous history of the substance and by changes of the environment. Slight rise of temperature and annealing ensures an increased sensitiveness and quick recovery.

4. The ascending portion of the curve of response is abrupt, whereas the fall during recovery is at first rapid and then comparatively slow; the curve of recovery is thus convex to the abscissa which represents time:

5. Under increasing intensity of stimulation, the amplitude of response undergoes an increase which reaches a limit.

6. Sub-minimal stimulus induces a response of opposite sign to that under moderate stimulation.

7. Under rapidly succeeding stimuli, the individual responses become fused; the curve rises to a maximum, when the force of restitution balances the force of distortion due to stimulation.

8. Under prolonged stimulation, the response tends to become reversed; during this process the reversal may become recurrent.

4. *The Strain Theory of Photographic Action*

The photographic effect of light is detected in a few cases only, when the induced change happens to be visible or is rendered visible on development; the image often disappears on account of self-recovery during darkness. The changes induced can, however, be followed in all its phases in the resulting curve of electric response. In this curve the period of overcoming molecular inertia corresponds to the induction period of photographic action; the automatic recovery explains relapse of the impressed image.

This impression can be rendered more permanent by molecular overstrain under strong and long-continued action of light, the recovery from overstrain being thus greatly prolonged. The fact that molecular strain induced by light is universal, is shown by images produced not merely on photographic plates, but also on sheets of ordinary metals (p. 213). Molecular impression produced in other ways than by light is seen in the inductoscripts and in the development of pressure marks.

Recurrent photographic reversals are produced under continued action of light similar to those under continuous mechanical stimulation (p. 215).

Owing to tendency towards self-recovery, the resulting effect does not solely depend on the total quantity of incident light, but also on the time-rate of illumination. Hence for the same duration of exposure, the photographic effects of intermittent and continuous illuminations are not the same (p. 217).

D. The Similarity of Response of Inorganic and Living Substances

A molecular upset is produced in inorganic substances by the impact of stimuli, electrical or mechanical. The response is recorded by methods of conductivity and electromotive variations.

In inorganic receivers for electric radiation, continuous stimulation induces fatigue which is removed after a period of rest. Prolonged rest, however, makes the receiver inert, and the lost responsivity is then only restored after a period of stimulation (p. 253). These characteristics are similar to those in the response of living substance.

Successive stimuli of equal intensity give rise to uniform inorganic responses. Superposition of stimuli causes incomplete or complete "tetanus" according to slow or quick frequency of stimulation (p. 256).

Certain chemical substances produce a great enhancement in the amplitude of response; these act as stimulants in inducing an increase of excitability (p. 274). Others produce a depression. The variation of excitability induced by various chemical substances, or different doses of the same substance can be detected by the Electric Comparator (p. 282). Slight differences of physico-chemical change in the same piece of metal are detected and recorded by the Electro-molecular Explorer (p. 287).

The effect of an identical chemical agent is modified by the dose of application, a minute dose often producing a reaction opposite to that of a large dose (p. 301). Poisons like oxalic acid cause a molecular arrest and 'kill' the response of metals (p. 303).

E. The Physiological Response of Plant

Among the manifestations in the life of the plant may be mentioned its irritability for response to external stimulation, its growth and its power of storing energy supplied by the environment.

1. *Electrical Response of ordinary Plants*

The power of response in plants has generally been regarded as confined to the sensitives like *Mimosa pudica*. Experimental investigations are described which prove that all plants and their different organs are fully sensitive, and that the characteristic electric response by induced galvanometric negativity given by them is in every way similar to the electric response of animal tissues (p. 309).

Successive equal stimulations give rise to uniform responses. Shortening of the intervening period of stimulation brings about fatigue, which is removed after a suitable period of rest. Stimulus singly ineffective becomes effective by summation of several. The amplitude of response increases with the intensity of stimulus till a limit is reached. Anæsthetics induce a depression of excitability. A large dose of chloroform and poisonous substances produce a permanent abolition of response with the death of the plant (p. 315). The response is also abolished when the plant is scalded to death (p. 314). The fatal temperature for the plant is about 60° C.

2. Response of Plant to the Stimulus of Light

The plant responds to the stimulus of light by contraction on account of which the directly stimulated side of a stem becomes concave seen in the positive heliotropic curvature of stems. The normal electromotive response under light is by an induced change of galvanometric negativity. I succeeded in devising another method by which the excitatory change of the plant-tissue is detected by a diminution of its electrical resistance. The most sensitive device for this purpose is the Quadrant Method which records response to light of so excessively short a duration as that emitted by a single spark (p. 320).

The amplitude of response, by resistivity variation, increases with the intensity light. Very dilute vapour of ether increases the excitability as demonstrated by the enhanced amplitude of response. Strong dose of chloroform, on the other hand, causes depression and death as indicated by gradual diminution and final abolition of response.

3. *The Vegetable Photo-electric Cell*

A very sensitive method of record of the action of light by the induced electromotive variation of galvanometric negativity is afforded by the photo-electric cell in which two similar leaves, immersed in an electrolyte, form the voltaic elements. There is no current in the cell when it is kept in the dark, but exposure of one of the two leaves gives rise to a responsive current. The amplitude of response increases with the intensity and duration of exposure to light. An abnormal positive response occurs when the physiological vigour of the specimen is feeble and below the normal.

In the green leaves two opposite reactions are simultaneously induced under the action of light; of these the A-reaction is associated with the building up process and storage of energy by assimilation; the D-reaction of break-down and expenditure of energy occurs under excitatory action of stimulus. The A-effect is often masked by the predominant D-reaction; the existence of A is demonstrated by the positive electric response exhibited by actively assimilating plants like Hydrilla; it is also shown as an after-effect on the cessation of stimulus (p. 330).

4. *Automatic Record of Response of the Photosynthetic Organ*

The living plant is in a state of unceasing activity, absorbing and storing energy from without, setting free and dissipating it from within. The expenditure of energy may be manifested in movement, or it may not be externally perceptible, being employed in working the internal mechanism of the body—such for instance, as the distribution of water, which as I have shown elsewhere* involves a considerable expenditure of energy. The fundamental importance of photosynthesis is, that it is the process by which the plant absorbs the energy it requires, the radiant energy of sunlight, and stores it in the form of latent or potential energy in the process. The energy so stored can readily be set free again and become kinetic by the chemical decomposition of the organic substances, manifesting itself in heat, electric current or movement.

All these changes are effected by the living protoplasm and are the expressions of its physico-chemical reactions. This is made clear by the observation that all the various manifestations of them that have been made accessible to investigation are affected in a similar manner by a given stimulus or change in internal or external conditions.

Automatic Recorder for Photosynthesis.—The estimation of the activity of photosynthesis, with water plants from the rate of evolution of oxygen is direct and requires no prolonged chemical analysis. The automatic record by the Electro-magnetic Writer of successive bubbles representing equal volumes of pure oxygen eliminates all personal error of observation. The method is so sensitive that records may be obtained from which it is possible to estimate the formation of quantities of carbohydrate as small as the millionth of a gramme (p. 333).

The automatic method of record that has been described, can also be utilised in physico-chemical investigations, such as the determination of the rate of evolution of a gas under controlled conditions of temperature, of concentration, of intensity of light, of catalytic agents and others, either separately or in combination.

* Physiology of the Ascent of Sap, 1922.

5. *Hourly variation of photosynthetic activity*

In the median range of the photosynthetic curve the increase of activity is proportional to the intensity of light. The latter is determined by the Self-recording Radiograph (p. 338). As regards the effect of rise of temperature, the increase of photosynthetic activity is uniform in the median range of temperature variation, there being an abrupt decline beyond the optimum. The combined effects of the factors of variation of light and temperature, explain the hourly variation of photosynthetic activity which is at its maximum at about 1 p.m. (p. 334).

6. *Effect of infinitesimal traces of chemical substances*

Investigations on the effect of infinitesimal traces of certain chemical substances show that they produce a very great increase in the activity of assimilation. The demonstration of this is of special interest since it enables us to understand the effect of infinitesimal quantities of vitamin on general assimilation and of hormones on physiological reaction.

The effect of minute quantity of formaldehyde in enhancing the activity is of special significance in regard to the possible formation of formaldehyde as the first product of photosynthesis. This substance is toxic only in a strong dose; before there could be any great accumulation of this substance in the cells it would have become polymerised into carbohydrate.

7. *Efficiency of photosynthetic storage of energy*

The estimates hitherto obtained indicate generally a very low efficiency; the experimental methods employed in this determination have been defective from absence of means for the exact measurement of the energy absorbed, and the energy stored in photosynthesis. The difficulties have been obviated by the new methods devised for the purpose. The energy absorbed is found by the Calorimetric method. The accuracy of the calorimetric determination was tested independently by results obtained with the highly sensitive Magnetic Radiometer (p. 360). The energy stored was simultaneously found from the volume of oxygen given out by the plant, the carbohydrate factor of which had been very carefully determined. The photosynthetic efficiency of the leaves of Hydrilla is fairly high, being about 7·4 per cent. (p. 336).

8. *The activity of growth*

The essential difficulty of the investigation arises from the extraordinary slowness of growth, the average rate of which is about $\frac{1}{100,000}$ inch per second, a length which is half that of a single wave of sodium light. Even with the magnifying growth recorders hitherto employed, it takes a very long time to detect and measure its rate. For accurate investigations on the effect of a given agent on growth, it is necessary to keep all other variable conditions, such as light and warmth, strictly constant during the whole period of the experiment. We can keep these conditions absolutely constant for only a few minutes at a time. Experiments which require several hours for their completion are, therefore, subject to serious errors which vitiate the results.

The only satisfactory method is one that reduces the period of the experiment to a few minutes; that, however, necessitates the devising of an apparatus for exceptionally high magnification, and for the automatic record of the magnified rate of growth.

The High Magnification Crescograph gives automatic record of growth under a magnification of ten thousand times (p. 348). With this it is possible to obtain growth-record in a time shorter than a second and determine its absolute rate, which in S. Kysoor is 0 95 μ per second, where μ represents micron or 0 001 mm.

Effect of variation of temperature.—The effect of rise of temperature in acceleration of growth can be determined in a few minutes (p. 349). It is thus possible to make accurate determinations of the optimum temperature for maximum growth and the minimum temperature for the arrest of activity.

Effect of Chemical agents.—The effect of manures, anaesthetics, drugs and poisons can be similarly determined in a few minutes and with unprecedented accuracy. The effect of a chemical agent is found to be modified by the dose of application (p. 351).

The Balanced Crescograph.—A still higher sensitiveness in recording the slightest change of growth was secured by the method of balance in which by a clock-work device, the plant is made to descend exactly at the same rate at which the growing tip of the plant was rising (p. 352). The rate of growth is thus accurately compensated and the recorder dots a horizontal line of balanced growth. The minutest change induced in the rate of growth by the environment is at once indicated by the upset of the balance shown by the up and down movements of the curve. The method is so extremely sensitive that it detects and records variations in the rate of growth so excessively minute as $\frac{1}{1500}$ millionth of an inch per second.

Wireless waves and growth.—The results obtained by the Balanced Crescograph prove that electric waves used in signalling through space are effective in modifying the rate of growth. The perceptive range of the plant is far greater than ours; it not only perceives but also responds to different rays of the vast ethereal spectrum.

Opposite reactions under feeble and strong stimulation. —This appears to be a universal phenomenon, characteristic of response of both inorganic and living substances under diverse modes of stimulation. This is seen in the responses of inorganic matter to electric radiation. In the positive class, *e.g.* Osmium in which the response to moderate stimulation is by a diminution of resistance, a subminimal stimulus induces a response by an increase of resistance (p. 137). Similar opposite responses under moderate and feeble stimulation are also exhibited by negative class of substance represented by Arsenic (p. 137). The electromotive response of metallic wires under mechanical stimulation also exhibits this characteristic (p. 204). A short-lived negative twitch is often observed preceding the normal response designated as positive. This is due to the fact that it takes a short time before the responding substance can absorb the whole amount of incident stimulus, the first moiety absorbed being sub-minimal (p. 181). This characteristic effect is exhibited not only by electromagnetic receivers (p. 189) but also by photo-electric cells responding to light (p. 190) and by strain cells under mechanical stimulation (p. 204).

In plants also similar reactions are observed. This is seen in the opposite effects of feeble and strong intensity of electric waves in enhancement and retardation of growth respectively (p. 355).

Parallel effects are also observed in regard to chemical stimulation of both inorganic and on living matter. The same reagent which in large doses causes a depression of excitability and abolition of response in metals, induces, on the other hand, a great enhancement of response when the dose is sufficiently minute (p. 301).

In the living plant, poisons produce death and permanent abolition of response. In minute doses, however, they induce a great enhancement of vital activity thus acting as a highly efficient stimulant in promotion of growth (p. 351).

The Magnetic Crescograph.—The magnification is very greatly increased by the Magnetic Crescograph which produces a magnification of about 50 million times; this order of magnification would lengthen a single wave of sodium light to 2,500 cm. (p. 357).

The Magnetic Radiometer.—This enables comparison of energy of every ray in the solar spectrum (p. 362).

F. Identity of Physiological Mechanism in Plant and Animal

A continuity of response having been established between the responses of inorganic matter on the one hand and living plants on the other, inquiry was continued to find out whether the fundamental physiological mechanisms were similar in plant and in animal life. The plant world affords an unique opportunity for studying the changes by which a simple and primitive organ becomes gradually transformed into one of greater complexity. The evolutionary process has been active not only in morphological differentiation, that is, in the development of new forms, but also in physiological differentiation, that is, in the development of specialised mechanisms for the performance of the various vital functions. There still exists a long prevalent idea that physiological mechanisms of animals and plants are fundamentally different. The evidence afforded by results of experimental investigations show that this idea is unfounded.

The most important characteristics of certain animal tissues are (1) *contractility* on account of which rapid movement is produced by muscular organ ; (2) *conductivity* or power of transmitting excitation to a distance and (3) *rhythmicity* or so called spontaneous movements.

Muscular organ in plants.—The functional similarity between the two contractile organs, pulvinus and muscle, is not confined to the manifestation of outward movement, but can be traced to the ultimate protoplasmic mechanism. There are three types of contractile organs distinguished by their rapidity of reaction. The wing-muscle of a bird of prey like the falcon is very active ; that of the goose is less active, while the muscle of the domestic fowl is almost inactive, its power of flight having been practically lost. The activity of animal muscle is found to be dependent on the presence and relative distribution of an active substance.

In the leaves of plants there are similarly three types of motor organ—active, semi-active and inactive. The first is exemplified by Mimosa pudica, the second by Neptunia oleracea ; and the third by the pulvinus of Phaseolus in which the movement is very feeble and extremely sluggish. By means of selective staining I succeeded in producing a sharp differentiation of the actively contractile from other inactive cells. In Mimosa the active substance is present in great abundance; in Neptunia the particular substance is quantitatively less and scattered. In the inactive Phaseolus the active substance is altogether absent.* The pulvinus of Mimosa may thus be regarded as functionally equivalent to an active animal muscle.

Nervous tissue in plants.—Some of the crucial tests for discrimination of nervous impulse are (1) that excitation is initiated for transmission by the characteristic polar action of a constant electric current; (2) that the velocity of transmission is increased within limits, by a rise of temperature; (3) that the transmission can be arrested temporarily or permanently by various physiological blocks. The conducting power is temporarily arrested during the passage of an electric current in a portion of the conducting tissue through which the impulse is being transmitted, the block being removed on the stoppage of the current; (4) that the conducting power is permanently abolished by poisonous solutions. The results of application of these crucial tests offer conclusive proof that the conduction in the plant is a phenomenon of protoplasmic excitation as in the nerve of the animal.

The velocity of transmission in plants is accurately determined by the Resonant Recorder by which time intervals as short as $\frac{1}{200}$ sec. can be recorded. The velocity of transmission is sometimes as high as 400 mm. per second. It is slower than the nervous impulse in higher, but quicker than in lower animals (p. 369).

Rhythmic tissue.—I have demonstrated elsewhere the remarkable similarity of rhythmic mechanism in

* Plant Autographs and their Revelations, 1927.

animal and plant.* In both, lowering of temperature slows down the pulsation culminating in an arrest. Rise of temperature to an optimum, on the other hand, enhances the frequency. Diminution of internal pressure causes a similar arrest in both. The rhythmic tissues in animal and plant have a long refractory period. In both, application of external stimulus has no effect during systolic phase of contraction, whereas an extra-pulsation is produced by stimulus during the diastolic phase of expansion (p. 372).

Records of rhythmic cardiac pulsation were obtained with Resonant Cardiograph which gives the most accurate record of the different rates of movement at different phases of the cardiac cycle (p. 371).

The effects of certain drugs are found to be remarkably similar on rhythmic tissues in animal and plant. Certain drugs thus cause in both a great depression of activity; subsequent application of a particular drug then causes a marked revival of activity.

A considerable portion of this volume deals with the optical properties of electric waves, the study of which has been facilitated by devices for the production of short waves and reliable means for their detection. Results have been obtained which show that electric radiation produces allotropic modification in matter analogous to those by visible light. The most unexpected results are those which demonstrate a continuity of response in the Living and Non-living.

The intricate mechanism of life can only be elucidated by extension of our power of investigation, often in the realm of the invisible. It is only from facts so

* Irritability of Plants, 1913.

ascertained that a fully satisfactory theory can be established in regard to diverse activities of life; it is not improbable that these will some day be ultimately traced to physico-chemical reactions.

Physics in a larger sense includes investigations on the reactions of matter, both inorganic and living. The methods of investigation are identical in the two cases. The various appliances described, the very high magnification and record of imperceptible movements, the automatic record of extremely short intervals of time and the rate of reaction, the measurement of energy of different rays of the solar spectrum and of the transformation and storage of the energy by the photosynthetic organ—these and others will also be found of value in the advancement of purely physical and physico-chemical investigations.

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